DEPARTMENT OF TRANSPORTATION

Evaluation of Safety and Mobility of Two-Lane Roundabouts

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University of Minnesota

July 2017

Research Project
Final Report 2017-30

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When looking at measures of fatal and severe-injury crashes, roundabouts have demonstrated improved safety performance compared to traditional signalized intersections. Despite this, when it comes to less severe crashes, multilane roundabouts fail to provide a similar benefit. Previous research into this topic has identified behaviors that are associated with crashes in two-lane roundabouts, with yielding violations and turn violations generally being the largest contributors to crashes. This study sought to build on that work by expanding the data collection effort to include more sites and relate the frequency of individual behaviors to specific design features. Ultimately, four roundabouts were chosen for data collection and analysis, with two of them being full 2x2 roundabouts and the other two half-2x2. These locations were University Dr. S and 5th Ave. S in St. Cloud (half-2x2), 185th St. W and Kenwood Trail in Lakeville (full-2x2), and TH-22 and Adams St. (half-2x2) and TH-22 and Madison Ave. in Mankato (full-2x2). In the last two, changes in traffic control were implemented to reduce failure-to-yield crashes, and the study compared the driver behavior before and after the interventions. In general, the collective results show that the problems observed in the earlier site are present in all of the other sites with scale variations prompted by geometric and traffic control design elements. For example, in the St. Cloud roundabout, an increased rate of right-from-inner-lane turn violations were observed, which can be attributed to the sharper deflection angles present. Additionally, from the aforementioned roundabout as well as the one in Lakeville, it was concluded that turn violation rates are affected on the single or multilane geometry of the links approaching the roundabout. Single-lane roads result in fewer left-from-outer-lane violations. Overhead lane designation signs result in reduced turn violations similar to the earlier studies' interventions in the approach lane markings. Unfortunately, apart from confirming the trend, no successful design or intervention was discovered regarding yield violations.</td></tr>
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EVALUATION OF SAFETY AND MOBILITY OF TWO-LANE ROUNDABOUTS

FINAL REPORT

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LIST OF ABBREVIATIONS

MnDOT....................Minnesota Department of Transportation
MTO....................Minnesota Traffic Observatory
PDO.................... Property Damage Only
TAP.................... Technical Advisory Panel

EXECUTIVE SUMMARY

When looking at measures of fatal and severe-injury crashes, roundabouts have demonstrated improved safety performance compared to traditional signalized intersections. This, coupled with their delay-reduction potential, has made roundabouts attractive to practitioners and has helped drive their adoption throughout the United States. Despite this, when it comes to less severe crashes, multilane roundabouts fail to provide the same benefit. In many cases, they actually come with increased rates of crashes resulting in property damage only. The prevalence of driver errors and property damage crashes at “2x2” roundabout conflict locations, where two entering through lanes cross two exiting through lanes, may deter agencies from implementing such designs in favor of single-lane roundabouts, which provide less mobility and shorter design life, or traffic signals, which have higher delays and are less safe. The effects of this can be seen across Minnesota, where several 2x2 roundabouts have recently been converted to 2x1 configurations by changing striping to reduce the number of available through lanes. At best, this is only a temporary solution, however, since the additional capacity will likely be needed in less than 20 years.

In the long term, a more effective solution to this problem requires determining why drivers are prone to certain mistakes and developing a design that can correct this behavior. Previous research into this topic has identified the following behaviors that are associated with crashes in two-lane roundabouts, with yielding violations and turn violations generally being the largest contributors to crashes:

- Yielding violations (entering vehicles failing to yield to cross traffic)
- Lane changes inside the roundabout
- Turn violations (e.g., right turns from the left-hand lane)
- Wrong-way movements

A previous observational before/after study conducted by the University of Minnesota focusing on a 2x2 roundabout in Richfield, MN, has demonstrated that changes to signs and lane markings of the roundabout significantly reduced the occurrence of some of these errors (Richfield et al., 2013). While that roundabout is atypical both in terms of design (pre-2009 MUTCD) and driver population (young suburban and commuter traffic), the results of the study are still encouraging, as they suggest that effective solutions for treating these common mistakes can be found as more data is collected and the problem becomes more well understood.

This study seeks to build on this work by expanding the data collection effort to include more sites, collecting observations of undesirable driving maneuvers at several of the remaining 2x2 roundabouts in Minnesota and relating the frequency of individual behaviors to specific design features. Ultimately, four roundabouts throughout the state were chosen for data collection and analysis, with two of being them fully multi-lane roundabouts with exclusively 2x2 conflict areas and the other two being partial multi-lane roundabouts including both 2x1 and 2x2 conflict areas. These locations are:

- University Drive South and 5th Avenue South in St. Cloud (partially 2x2)
- 185th Street West and Kenwood Trail in Lakeville (fully 2x2)

- TH-22 and Adams Street in Mankato (partially 2x2)
- TH-22 and Madison Avenue in Mankato (fully 2x2)

These roundabouts have all been built recently and are based on the latest design standards, which prescribe much larger deflection angles for entrances and exits compared to Richfield, but serve very different driver types and exhibit enough variation between roundabouts to help highlight which design features are most effective at reducing a given type of violation.

This study largely follows the same experimental design successfully executed in the previous study with some updates to automate parts of the process as well as to extract more data for analysis. This methodology involves the collection of several days' (or more) of video observations and the identification of all the driving violations performed by the drivers. Whereas the earlier study relied on manual reduction of the video records, this process was automated for the current study by using the computer vision application, TrafficIntelligence (Jackson et. al, 2013), to extract vehicle trajectories directly from video then using a custom trajectory analysis to tabulate data for analysis. This not only reduced the time required to process the video, but it also allowed turning movements and speeds to be output for every vehicle observed using the roundabouts. This provided increased ability to control for the effect of traffic in the roundabout on the rates of undesirable behaviors and allowing the underlying relationship with design features to be seen.

The analysis of this data focused on yielding and turn violations, which are the most commonly, cited reasons for crashes occurring in two-lane roundabouts. Once violation and volume data were extracted, the data was analyzed to determine how the rates of these violations vary by location and relevant design features. In regards to Turn Violations, the roundabout in St. Cloud presents some differences when compared with the roundabout in Richfield. Specifically, left-from-outer-lane violations, which are the source of the most serious crashes, exhibit noticeably lower rates. Several possible causal factors for this were explored with no revealed correlation. The one geometrical difference in this roundabout is that all roads approaching the roundabout have one lane per direction upstream of the roundabout entrances while, in Richfield, all roads had two lanes per direction upstream of the roundabout. One can hypothesize that, in the case of left turns, drivers instinctively choose to stay close to the left curb and, by extent, the inner lane of the approach. In the Lakeville roundabout, the left-from-outer-lane violations are similar to Richfield, except on the approaches where the upstream direction has one lane per direction, reinforcing the aforementioned hypothesis. Both of the Mankato roundabouts have overhead lane designation signs, which seems to be directly related to much lower turn violations observed as compared to Richfield and the other roundabouts in this study.

This study has put extra effort into understanding the causes of yield violations since the earlier study failed to produce a traffic control plan that can reduce their rate of occurrence. Unfortunately, this study, too, did not produce insight on the nature of the problem or potential solutions. In the St. Cloud and Lakeville roundabouts, the rates of yield violations followed more or less the same rates as in the earlier study and followed the familiar pattern of higher rates in failures to yield to the inner lane of the roundabout. The failure-to-yield (FTY) rates in the in the approaches from Adams Street also occurred at similar or slightly higher levels. However, the TH-22 NB approach presented significantly lower rates, almost 10 times lower, while the TH-22 SB approach was somewhere in between. The latter has only one lane of cross traffic to yield to.

The results are a little more complicated at the Madison Ave Roundabout. Specifically, the approach from Madison EB exhibited an initial rate that was slightly lower than the norm compared to the earlier study and was sharply reduced after the learning period was over. Unfortunately, in the period after the traffic control changes, it climbed again to nearly the same level as during the learning period though that rate was still lower than the norm. There is no real explanation for this other than the traffic control changes not having the desired effect. The approach from TH-22 SB follows the same pattern as the Adams Roundabout, with the FTY rate being significantly lower than any other roundabout in the study and remaining unchanged throughout the three study periods. The conclusion is that the traffic control changes implemented at the Mankato roundabouts did not produce any significant improvements on the yield violation problem.

Chapter 1: Introduction

When looking at measures of fatal and severe-injury crashes, roundabouts have demonstrated improved safety performance compared to traditional signalized intersections. This, coupled with their delay-reduction potential, has made roundabouts attractive to practitioners and has helped drive their adoption throughout the United States. Despite this, when it comes to less severe crashes, multilane roundabouts fail to provide the same benefit. In many cases, they often come with increased rates of crashes resulting in property damage only. The prevalence of driver errors and property damage crashes at "2x2" roundabout conflict locations, where two entering through lanes cross two exiting through lanes, may deter agencies from implementing such designs in favor of single-lane roundabouts, which provide less mobility and shorter design life, or traffic signals, which have higher delays and are less safe. The effects of this can be seen across Minnesota, where several 2x2 roundabouts have recently been converted to 2x1 configurations by changing striping to reduce the number of available through lanes. At best, this is only a temporary solution, however, since the additional capacity will likely be needed in less than 20 years.

In the long term, a more effective solution to this problem requires determining why drivers are prone to certain mistakes and developing a design that can correct this behavior. Previous research into this topic has identified the following behaviors that are associated with crashes in two-lane roundabouts, with yielding violations and turn violations generally being the largest contributors to crashes:

- Yielding violations
    - Failing to yield to left-lane cross traffic
    - Failing to yield to right-lane cross traffic
    - Failing to yield to both lanes of cross traffic
- Lane changes
    - Changing lanes at entrance
    - Changing lanes at exit
    - Straddling both lanes
    - Cutting straight across
- Turn violations
    - Making illegal right turn from left-hand lane
    - Making illegal left turn from right-hand lane
- Wrong way

In addition to this, a previous observational before/after study focusing on a 2x2 roundabout in Richfield, MN, has demonstrated that changes to signs and lane markings of the roundabout can significantly reduce the occurrence of some of these errors (Richfield et al., 2012 and 2013). While that roundabout is atypical both in terms of design (pre-2009 MUTCD) and driver population (young suburban and commuter traffic), the results of the study are still encouraging, as they suggest that effective solutions for treating these common mistakes can be found as more data is collected and the problem becomes more well understood.

This study seeks to build on this work by expanding the data collection effort to include more sites, collecting observations of undesirable driving maneuvers at several of the remaining 2x2 roundabouts in Minnesota and relating the frequency of individual behaviors to specific design features. Ultimately, four roundabouts throughout the state were chosen for data collection and analysis, with two of them full 2x2 roundabouts and the other two half-2x2 (where three approaches have two lanes). These locations are:

- University Drive South and 5th Avenue South in St. Cloud (partially 2x2)
- 185th Street West and Kenwood Trail in Lakeville (fully 2x2)
- TH-22 and Adams Street in Mankato (partially 2x2)
- TH-22 and Madison Avenue in Mankato (fully 2x2)

These roundabouts have all been built recently and are based on the latest design standards, which prescribe much larger deflection angles for entrances and exits compared to Richfield, yet serve very different driver types. They also exhibit enough variation between roundabouts to help highlight which design features are most effective at reducing a given type of violation.

This study largely follows the same experimental design successfully executed in the “Before and After Study of Lane Restriction Marking and Signing at the Portland and 66th St Roundabout” project, with some updates to automate parts of the process as well as to extract more data for analysis. This methodology involves the collection of several days’ (or more) of video observations and the identification of all the driving violations performed by the drivers. The earlier study relied on manual reduction of the video records, which is very time consuming but produces reliable data if the reduction process is well managed. For the current study, this process was automated by using computer vision software to extract vehicle trajectories directly from video, then using a custom trajectory analysis to tabulate data for analysis. This not only reduced the time required to process the video, but it also allowed turning movements and speeds to be output for every vehicle observed using the roundabouts. This provided increased ability to control for the effect of traffic in the roundabout on the rates of undesirable behaviors and allowing the underlying relationship with design features to be seen.

The analysis of this data focused on yielding and turn violations, which are the most commonly cited reasons for crashes occurring in multi-lane roundabouts. Once violation and volume data was extracted, the data was analyzed to determine how the rates of these violations vary with the location and relevant design features. The following report describes the project in detail, providing an overview of the roundabouts selected for study, the methodology used to extract and analyze the data, and a discussion of the results of the analysis.

Chapter 2: Roundabout Selection and Engineering

During the pre-contract Technical Advisory Panel (TAP) meeting, possible sites for data collection were discussed. At that point, the only two immediately available roundabouts of interest were in St. Cloud at the intersection of University Drive South and 5th Avenue South (Figure 1) and in Bloomington at the interchange of TH-169 and I-494 (Figure 2). During the first TAP meeting, mentions of a few roundabouts that were going to be constructed in the near future were made. These roundabouts included the one on the interchange of CSAH-101 and CSAH-61 in Chanhassen, MN (Figure 3) and a pair of roundabouts in Mankato along TH-22. During the projects preliminary engineering effort, the research team collected information on all of the aforementioned locations. Although the roundabouts in Chanhassen and Bloomington did not fit the requirements for this study, the study of the plans for the Mankato roundabouts (Figure 4) showed that the roundabout at the intersection of Madison Avenue and TH-22 is exactly what this study needed while one approach at Adams Avenue was also compatible with the objectives of the study and one other had an interesting intermediate design (left-only inner lane). Additional effort over the course of this project unveiled another to-be-completed roundabout in Lakeville, MN (Figure 5) that matched the study requirements and thus was added as a fourth site.

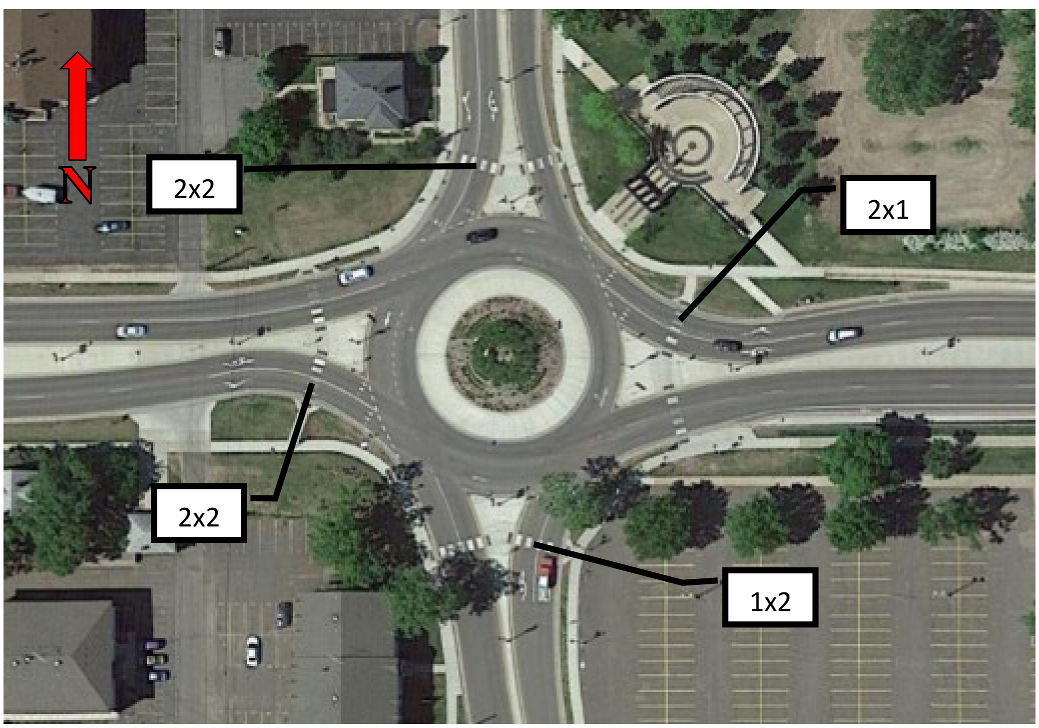

Figure 1: University Dr. S (running east/west) and 5th Ave. S (running north/south) in St. Cloud, MN (45.549482, -94.154587)

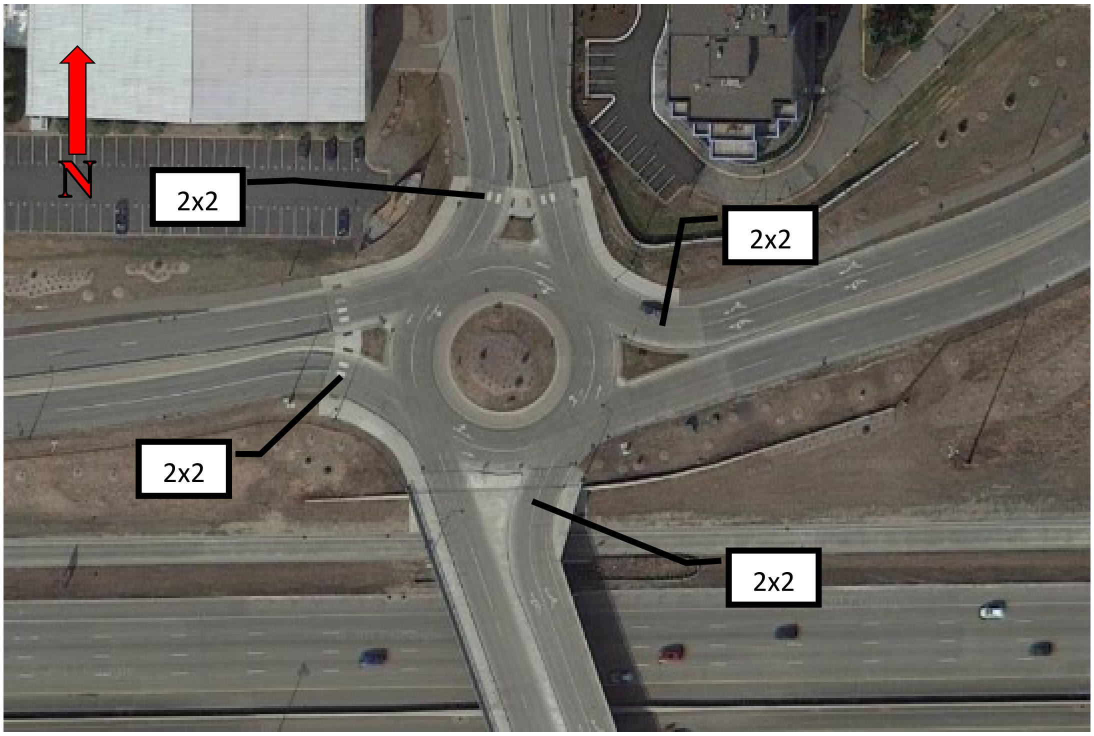

Figure 2: Viking Dr./W 78th St. (running east/west) and Washington Ave. (running north/south) in Bloomington, MN (44.860029, -93.398853)

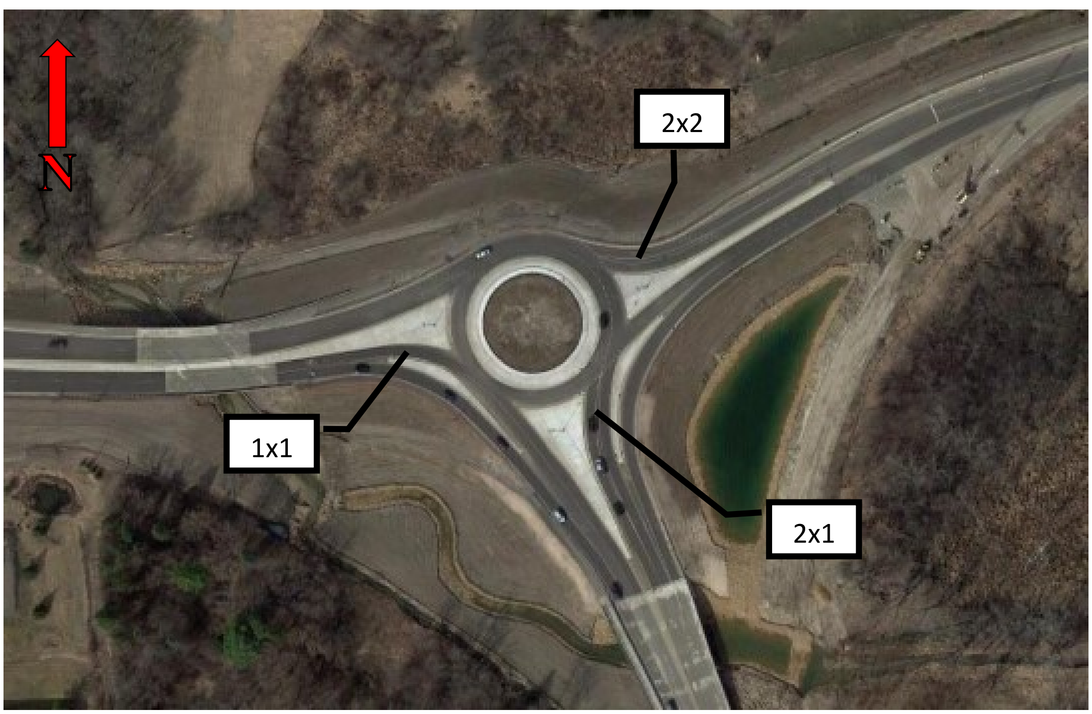

Figure 3: CSAH-61 (running east/west) and CSAH-101 (running north/south) in Chanhassen, MN (44.812119, -93.538929)

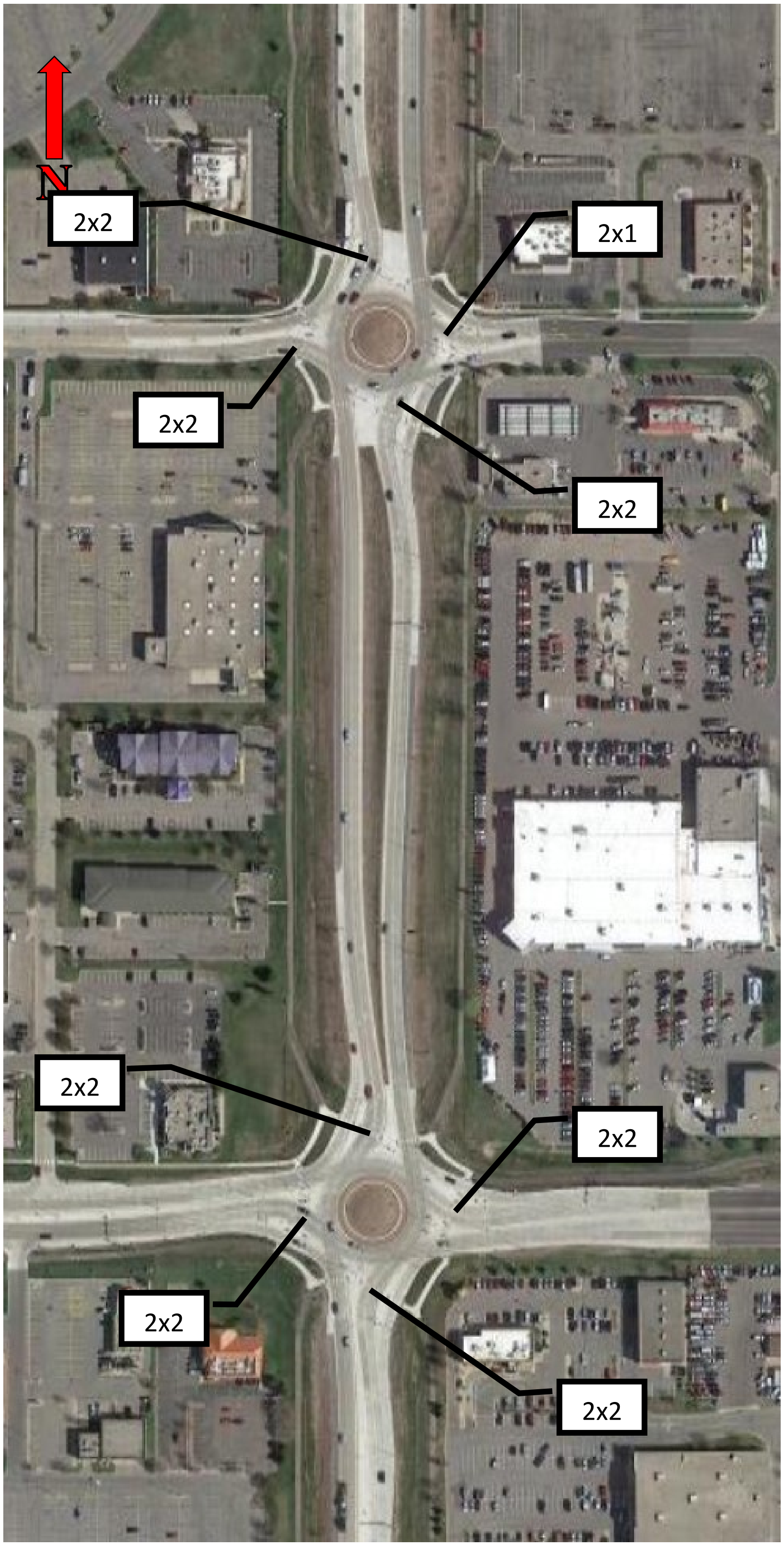

Figure 4: Madison Ave. (running east/west to the north), Adams St. (running east/west to the south), and TH-22 (running north/south) in Mankato, MN (44.168826, -93.949056)

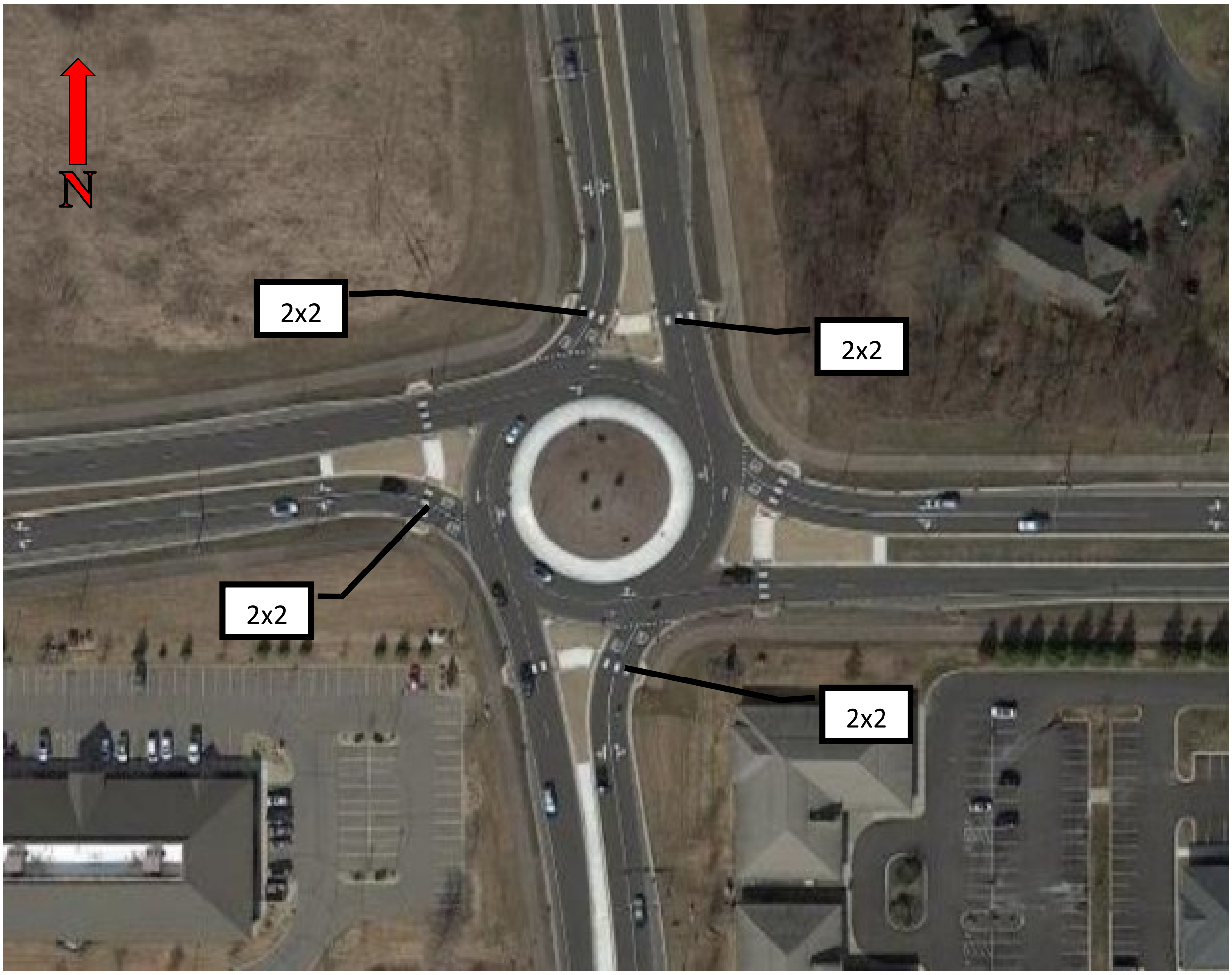

Figure 5: 185th St W (running east/west) and Kenwood Trail (running north/south) in Lakeville, MN (44.681446, -93.278054)

Chapter 3: Roundabout Historical Crash Records

This chapter summarizes the analysis of crash records from the three original roundabouts in St. Cloud and Mankato. For the St. Cloud roundabout, because crash records were not available at the local level, it became necessary to gain access in the Department of Public Safety (DPS) crash records database. This was a lengthy process of training and approvals because it involves access of personal, identifiable information. The Mankato roundabouts are newly constructed and went into use on August 25th, 2015. District 7 MnDOT engineer, Scott Thompson provided frequent updates of all crashes in the two roundabouts along with comments regarding the probable cause. Not all of the crash reports have the aforementioned information so the nature of the crashes was verified through the DPS database until the date of available records. Obtaining all records from the Mankato police department or the State Patrol was deemed unnecessary.

The aim of this effort was twofold: to establish, for the St. Cloud roundabout, a crash frequency from before it was built so the potential increase in crashes can be highlighted and, covering all locations, to determine the frequency of crash types on each roundabout.

3.1 ST. CLOUD ROUNDABOUT

The St. Cloud roundabout is located on the corner of University Drive and 5th Avenue South. In 2011, it was converted from a four-way signal controlled intersection to a partially 2x2 roundabout. The crash records between 2005 and 2011 show that intersection conflicts were not a cause for crashes with most of the 18 crashes on that period being rear-ends on vehicles caught up in a signal queue. Between 2011 and April of 2015 there were 42 total crashes which is a considerable increase regardless of any statistical considerations. Of these 42 crashes, 17 crashes were either weather related, rear-ends at the approaches, or for unrelated to the roundabout causes (alcohol, loss of control, etc.) Of the types of crashes related to the violations investigated in this study, the records show that yield violations are the predominant factor resulting in 20 crashes while 5 crashes were the result of turning left from the right-hand lane. Of the yield violations, the most common excuse was that drivers thought the vehicle on the inside lane was going to turn left (continue circulating) rather than exit, followed by inattention or completely missing the yield sign. In all cases the assumption was that the vehicle on the inside lane was going to turn left (continue circulating) rather than exit.

Compared to the Richfield roundabout, the St. Cloud roundabout has a significantly higher proportion of crashes related to yield violations than to turn violations.

3.2 MANKATO ROUNDABOUT 1: TH-22 AND ADAMS STREET

The first and smaller of the two roundabouts studied in Mankato, MN, is located at the intersection of TH-22 and Adams Street. On August 25, 2014, the conversion of the intersection from a four-way signalized intersection with left turn pockets to a partially 2x2 roundabout was completed. The crash data quoted in this report are from records provided by District 7.

While video was being recorded at Mankato Roundabout 1, 12 crashes were reported. Table 1 shows the crash data for both roundabouts. For some of the crashes, it was not possible to find them in the video so the comments were based on the DPS crash reports. For the crashes that occurred after video collection was completed, the respective causes of those crashes were determined using the DPS crash when possible. It should be noted that accessing data in the DPS database proved difficult and, at times, unreliable. For example, some crashes observed on camera were not found in the database while some crashes listed in the database were not in the list of crashes provided by the District 7 office. The main cause of these discrepancies is the fact that the configuration of the DPS site does not allow for easy querying of crashes due to the fact that they are stored by county and route thereby resulting in a large number of possible records for a given event.

Based on video records collected during the study and the DPS site at the time of publishing, there were 39 crashes between August 28th, 2014, and May 3rd, 2015, though there is a possibility that some of the most recent crashes have not been added to the database. From these 39 crashes 6 had no report associated or had an unrelated cause. From the 33 remaining, 3 crashes were related to Turn violations and 25 were due to failure to yield or yield violations (some yield violations resulted in rear-end crashes). The remaining 5 crashes were attributed to drivers' misunderstanding regarding the use of the inside lane on the south side of the roundabout and the resulting conflict with vehicles exiting to eastbound direction of Adams Street. More details on this subject will be discussed later in this report.

3.3 MANKATO ROUNDABOUT 2: TH-22 AND MADISON AVENUE

The second and larger of the two roundabouts studied in Mankato, MN, is located at the intersection of TH-22 and Madison Avenue. On August 25, 2014, the conversion of the intersection from a four-way signalized intersection with left turn pockets to a fully 2x2 roundabout was completed. Table 1 presents the crash data for crashes captured on video. While video was recorded at Mankato Roundabout 2, 21 crashes were reported.

Based on video records collected during the study and the DPS site at the time of publishing, there were 47 crashes between August 28th, 2014, and May 7th, 2015, though there is a possibility that some of the most recent crashes have not been added to the database. Of these 47 crashes, 7 had no report associated or had an unrelated cause. Of the 40 remaining crashes, 5 were related to turn violations and 35 were related to yield violations (some yield violations resulted in rear-end crashes).

3.4 LAKEVILLE ROUNDABOUT

The Lakeville roundabout was introduced last in the study and data were collected shortly after it was opened. Unfortunately this prevented the collection of crash data.

Table 1: Crash Incident Log (till 12-02-2014)

Date	*Time*	*Location*	*Cause*	*Found*	*Notes*	*Description*
8/28/2014	1757	TH-22 & Adams		NO	Possibly out of Frame	Possible Yield violation resulting in a rear-end
9/9/2014	1348	TH-22 & Adams	Illegal maneuver/Failure to yield	YES	Crash at 13:42:03 NVR Time.	Silver Truck coming from the left lane of eastbound Adams street appears to have realized that they could not proceed straight through the roundabout in that lane. They switched to the right lane at the yield line and hit a silver sedan on the left lane of the roundabout heading for southbound TH22.
9/12/2014	1352	TH-22 & Adams	Failure to Yield	YES	Crash at 13:46:39 NVR time.	
9/18/2014	1235	TH-22 & Adams	Failure to Yield	YES	Crash Happens out of Frame can see police response	
10/3/2014	1413	TH-22 & Adams	Failure to Yield	YES	Crash at 14:02:57 NVR time.	Black SUV coming from left lane of southbound TH22 going to south bound TH22 hit by Maroon SUV entering from eastbound Adams St right lane.
10/8/2014	1223	TH-22 & Adams	Failure to Yield	YES	Crash at 12:16:43 NVR Time.	Black sedan coming from left lane of eastbound Adams street heading for north bound TH22 hit by red sedan entering from left lane of westbound Adams St.
10/9/2014	1158	TH-22 & Adams	Rear-end	NO		Rear-end due to yield violation
10/11/2014	1057	TH-22 & Adams	Illegal maneuver/Enter from right turn lane	YES	Crash at 10:48:18 NVR Time.	A red truck pulled into the roundabout from the dedicated right turn lane of southbound TH22 to westbound Adams Street The truck caused a sliver sedan to break suddenly on the left lane of the roundabout heading toward east Adams Street. A dark sliver sedan heading southbound on TH22 accelerated into the intersection hitting the silver sedan who had come to a stop.
10/16/2014	1426	TH-22 & Adams	Failure to Yield	YES	Crash at 15:24:59 NVR time (NVR is one hour ahead)	
10/17/2014	1911	TH-22 & Adams	Failure to Yield	YES	Crash at 20:06:45 NVR time (NVR is one hour ahead)	
10/19/2014	1730	TH-22 & Adams	Failure to Yield	YES	Crash at 18:28:53 NVR time (NVR is one hour ahead)	Motorcycle cut off
10/24/2014	1524	TH-22 & Adams	Failure to yield	NO	Major slowdown outside of frame at 16:07:30 (NVR is one hour ahead)	
8/28/2014	1105	TH-22 & Madison		NO		No crash record

Date	Time	Location	Cause	Found	Notes	Description
8/29/2014	1339	TH-22 & Madison	Failure to Yield; Inattentive	NO		
9/1/2014	1704	TH-22 & Madison	Inattentive	NO		
9/6/2014	2004	TH-22 & Madison	Left Turn from right lane	NO	Camera Off line	
9/9/2014	1121	TH-22 & Madison	Failure to Yield	YES	Crash at 11:19:50 NVR time	
9/9/2014	1551	TH-22 & Madison	Failure to Yield; Inattentive	YES	Crash at 15:46:49 NVR time	
9/17/2014	1549	TH-22 & Madison	Failure to Yield	YES	Crash at 15:44:23 NVR time	
9/20/2014	1716	TH-22 & Madison	Failure to Yield	NO		
9/26/2014	2209	TH-22 & Madison	Failure to Yield	NO	Camera stops recording at 21:00	
10/10/2014	1520	TH-22 & Madison	Failure to Yield	YES	Crash at 15:14:43 NVR time	
10/13/2014	1812	TH-22 & Madison		NO		
10/13/2014	2023	TH-22 & Madison	Failure to Yield	YES	Crash at 20:15:25 NVR time	
10/14/2014	917	TH-22 & Madison		NO		
10/14/2014	1554	TH-22 & Madison	Illegal Maneuver/left turn from right lane	YES	Crash at 15:49:08 NVR Time	A sliver sedan coming from the right lane of eastbound Madison Avenue attempted to make a left turn to northbound TH22 from the right lane of the roundabout. The silver sedan hit a black truck that was in the left lane of the roundabout that entered at the same time and was proceeding straight through the roundabout to continue on eastbound Madison Avenue.
11/6/2014	1022	TH-22 & Madison	Failure to Yield	YES	Crash at 10:15:25 NVR Time	
11/20/2014	938	TH-22 & Madison	Failure to Yield	YES	Crash at 09:31:54 NVR Time	
11/20/2014	1602	TH-22 & Madison	Failure to Yield	YES	Crash at 15:57:56 NVR Time	
11/21/2014	557	TH-22 & Madison	Failure to Yield	YES	Crash at 05:52:40 NVR Time	
11/21/2014	804	TH-22 & Madison	Wide entering of semi	NO		
11/21/2014	1045	TH-22 & Madison	Failure to Yield	NO		
11/21/2014	1330	TH-22 & Madison	Failure to Yield	YES	Crash at 13:26:48 NVR Time	

3.5 DISCUSSION OF CRASH DATA AND INITIAL OBSERVATIONS

The Mankato roundabouts generate crashes predominately due to yield violations. Crashes due to Turn violations are an even smaller percentage as compared to the St. Cloud roundabout. The Mankato roundabouts have two major differences from the St. Cloud and Richfield roundabouts. The first difference is the use of large overhead lane directional signs to reinforce the message describing which is the appropriate lane for each destination in an attempt to reduce confusion by drivers. The second difference is the existence of free right turn lanes in the Mankato roundabouts which separate that flow from the through and left as well as prompts the extension of the solid lane markings a little further than what is currently in St. Cloud and what was originally the case in Richfield.

Having identified yield violations as the predominant cause of crashes in Mankato, the research team, the TAP, and District 7 engineers proposed a test regiment where the yield signs were to be altered in different ways. More details on this can be found in the Chapter 8.

It is important to note that Mankato Roundabout 1 has exhibited a unique problem. This roundabout is not a full 2x2 as only two sides (east & west) have two lanes whereas south side has one left-turn-only lane and one lane that exits and the north side has only one lane. The problem is observed in the south side where the inside lane only allows left turns and the outside lane only allows through movements. A large number of drivers do not realize this restriction and use the left lane to go straight and exit thereby coming into conflict with the vehicles in the right lane since the exit only has one receiving lane. The problem was observed very quickly and some attempts in restriping the lane were made with no observable change. From the initial observations, it was realized that it is predominantly vehicles originating from southbound TH-22 that make this mistake whereas the vehicles from eastbound Adams Street very rarely use the left lane to go straight. It seems that the vehicles making a left turn “hug” the central island curb and do not observe the lane markings. During the brainstorming sessions, some methods to communicate this rule more clearly to drivers were proposed but no such changes were implemented. It was also added that this observation suggests that even with a “notched” central island, the geometry and striping might not be sufficient to get drivers to spiral out to an outer lane prior to exiting. This finding has implications for staged implementation of roundabouts (trying to reduce the number of available lanes until such time that they are needed), because it indicates that treatments adjacent to the central island may not be sufficiently effective.

Chapter 4: Deployment of Data Collection Equipment

In contrast to the previous deployments at roundabouts by the Minnesota Traffic Observatory (MTO) in 2010, 2011, and 2012, a new set of cameras and recording devices were developed to better balance the needs of the new sites and study objectives. Specifically, in past deployments, the cameras were mounted on a mast trailer located in the center island of the roundabout. At all of the sites other than the Mankato Roundabout 2 where only specific approaches were of interest, cameras mounted on light posts to the side of each approach were used. At Mankato Roundabout 2, a single 360-degree camera was installed on a pole at the northwest corner of TH-22 and Madison Avenue. Installing cameras on the outside of the roundabouts had the benefit of providing the computer-vison-based vehicle detection system to be used with larger, less distorted vehicles. Additionally, this system expedited the deployment of the cameras by not requiring a variance to local regulations prohibiting trailers in the center of a roundabout and by providing an easy source of power from the light posts. The following sections each outline the equipment deployment at one of the four roundabouts observed as part of this study.

4.1 MANKATO: ROUND ONE

Cameras were deployed at the two roundabouts in Mankato, MN, (Figure 6) in the Fall of 2014. In both roundabouts, the surveillance equipment was mounted on light posts as shown in Figure 7. The recording equipment was housed inside a weather-resistant housing installed by MnDOT at the base of the pole that provided 24/7 power as shown in Figure 8. The equipment consisted of a network video recorder (NVR) to record the camera feeds and an uninterruptible power supply (UPS) to protect against any brown-outs and provided short-term emergency power. External cables from the enclosure to the cameras provided power and data for the cameras and were secured at regular intervals along the length of the pole up to final install height of the cameras at approximately 20 feet. In the case of the Mankato Roundabout 1, two surveillance cameras were deployed whereas only one camera with a 360-degree lens was deployed at Mankato Roundabout 2.

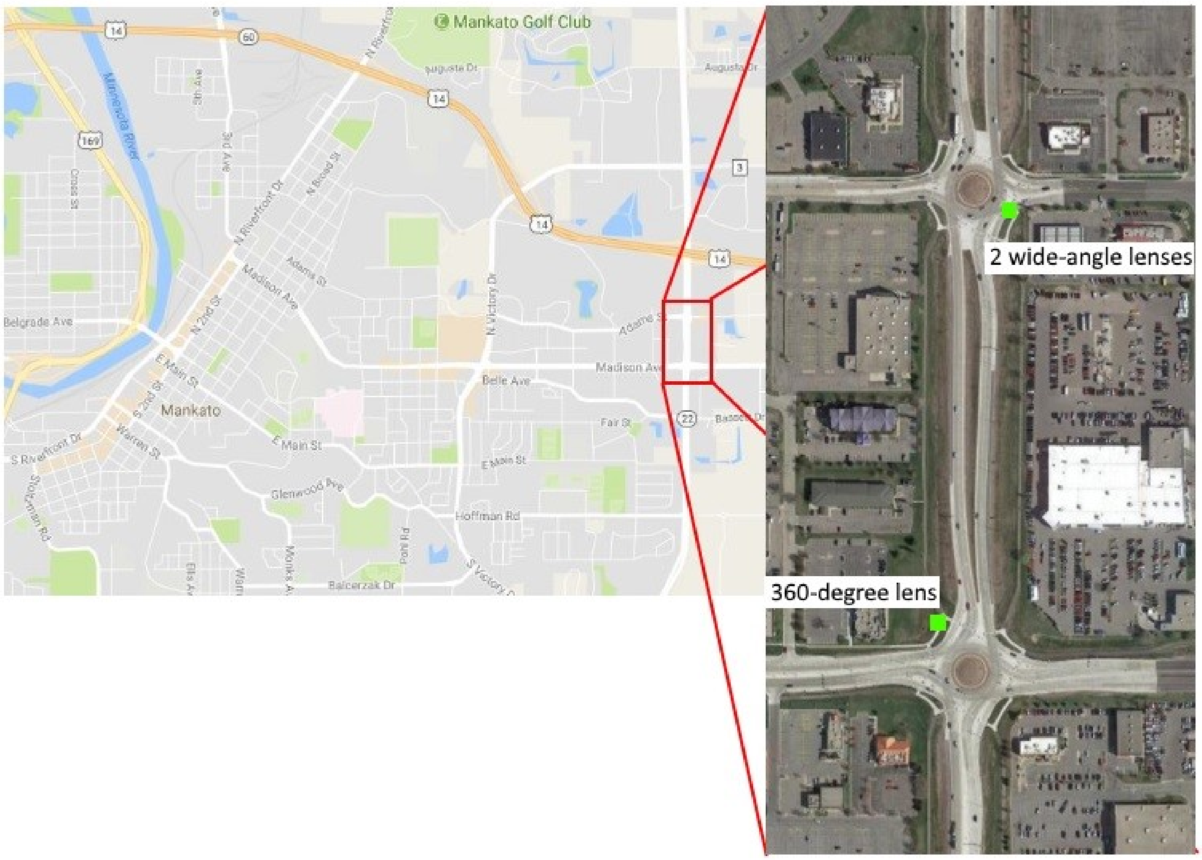

Figure 6: Mankato Roundabout 1 (to the north) and Mankato Roundabout 2 (to the south) with camera locations labeled.

Figure 7: Cameras deployed at Mankato roundabouts. Left is the 360-degree camera covering the intersection of TH-22 and Madison Avenue. Right is the two wide angle cameras covering the intersection of TH-22 and Adams Street.

Figure 8 Local video recording box installed at the base of the two light poles used shown closed (left) and up-close (right).

At Mankato Roundabout 1, two wide-angle cameras were deployed – one to capture the eastbound approach and the southern and western portions of the roundabout (Figure 9) and a second to capture the northbound approach and the east portion of the roundabout (Figure 10). At Mankato Roundabout 2, a single camera 360-degree lens camera was deployed to collect video of the entire roundabout (Figure 11).

Figure 9. Mankato Roundabout 1 view 1 - west and south portions of the roundabout.

Figure 10. Mankato Roundabout 1 view 2 - south and east portions of the roundabout.

Figure 11. Mankato Roundabout 2 - note that north is toward the bottom of the image.

4.1.1 Observation Periods

The surveillance equipment noted above was deployed on August 25th, 2014, to coincide with the opening of the two roundabouts. From that date through December 11th, 2014, video data was collected with minimal downtime. Recordings focused on daylight hours for all days of the week, although the particular start and end times varied. Recordings were adjusted to capture all 24-hours for the Thanksgiving weekend in order to capture traffic related to heavy shopping events at local malls. In all, approximately 100 usable days' worth of video was recoded.

4.2 MANKATO: ROUND TWO

Following signage changes at the two roundabouts in Mankato, video data were collected for approximately one month during Fall of 2015. Following the end of the previous data collection in December 2014, the recording devices were retrieved but the cameras were left in place. Once the signage changes had been implemented, the recording devices were returned to the site and data collection resumed on September 17th, 2015, however one of the camera lenses had lost focus requiring another visit to the site on September 25th, 2015. This camera, at Mankato Roundabout 1, was also reoriented at that time to provide a better view of vehicles entering the roundabout from the northbound approach of TH-22. Both of the two wide-angle cameras were repositioned so as to capture the eastbound and southbound approaches (Figure 12) and the northbound approach (Figure 13), with data collection focusing on the two-lane segments of the roundabout. The orientation of the camera viewing the northbound approach was adjusted to provide an expanded view of this approach. The 360-degree camera at Mankato Roundabout 2 remained in the same position.

Figure 12: View from camera of the eastbound and southbound approaches of the Mankato Roundabout 1.

Figure 13: View from camera of the northbound approach of the Mankato Roundabout 1.

4.2.1 Observation Periods

Recording resumed on September 17th, 2015. On September 25th, the camera observing the northbound approach of the Mankato Roundabout 1 was reoriented to improve the view of vehicles entering from this approach. Because this camera had lost focus between the deployments, the video it captured between the 17th and 25th was of somewhat reduced quality. From September 25th through October 23rd of 2015, video data were collected from all sites with no significant downtime. Recordings focused on daylight hours for all days of the week. Figure 14 below includes a breakdown of the recording times captured from each location by date. Video was recorded at each site from 6 AM to 9 PM unless otherwise indicated. In all, approximately 36 useable days' worth of video was collected.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
			Madison: Adams EB/SB: Adams NB:	**17 September** 16 - 21 16 - 21 16 - 21	**18** 6 - 21 6 - 21 6 - 21	**19**
20	**21**	**22**	**23**	**24**	**25** *View Adjustment*	**26**
27	**28**	**29**	**30**	**1 October**	**2**	**3**
4	**5**	**6**	**7**	**8**	**9**	**10**
11	**12**	**13**	**14**	**15**	**16**	**17**
18	**19**	**20**	**21**	**22**	**23** 6 - 10 6 - 10 6 - 10	

Figure 14. Video recorded at the Madison Avenue and Adams Street roundabouts from 9/17/15 to 10/23/15 (times in 24-hour format).

4.3 ST. CLOUD

The St. Cloud roundabout is located at the intersection of University Drive South and 5th Avenue South at the western edge of the St. Cloud State University campus (Figure 15). The roundabout was opened to traffic in 2011 and preliminary task reports showed a marked increase in Property Damage Only (PDO) crashes consistent with the trend identified at other previously-studied roundabouts. This roundabout, similar to Mankato Roundabout 1, is not a full 2x2 design but it does have two approaches with 2x2 conflicts which were the focus of data collection, two of the MTO's field-recording stations were placed at the edge of the roundabout at the northwest and southwest corners of the intersection (Figure 16). The stations consist of a camera, timer, recording device with local storage, and battery power with a heavy-duty metal housing and extendable mast for elevating the camera.

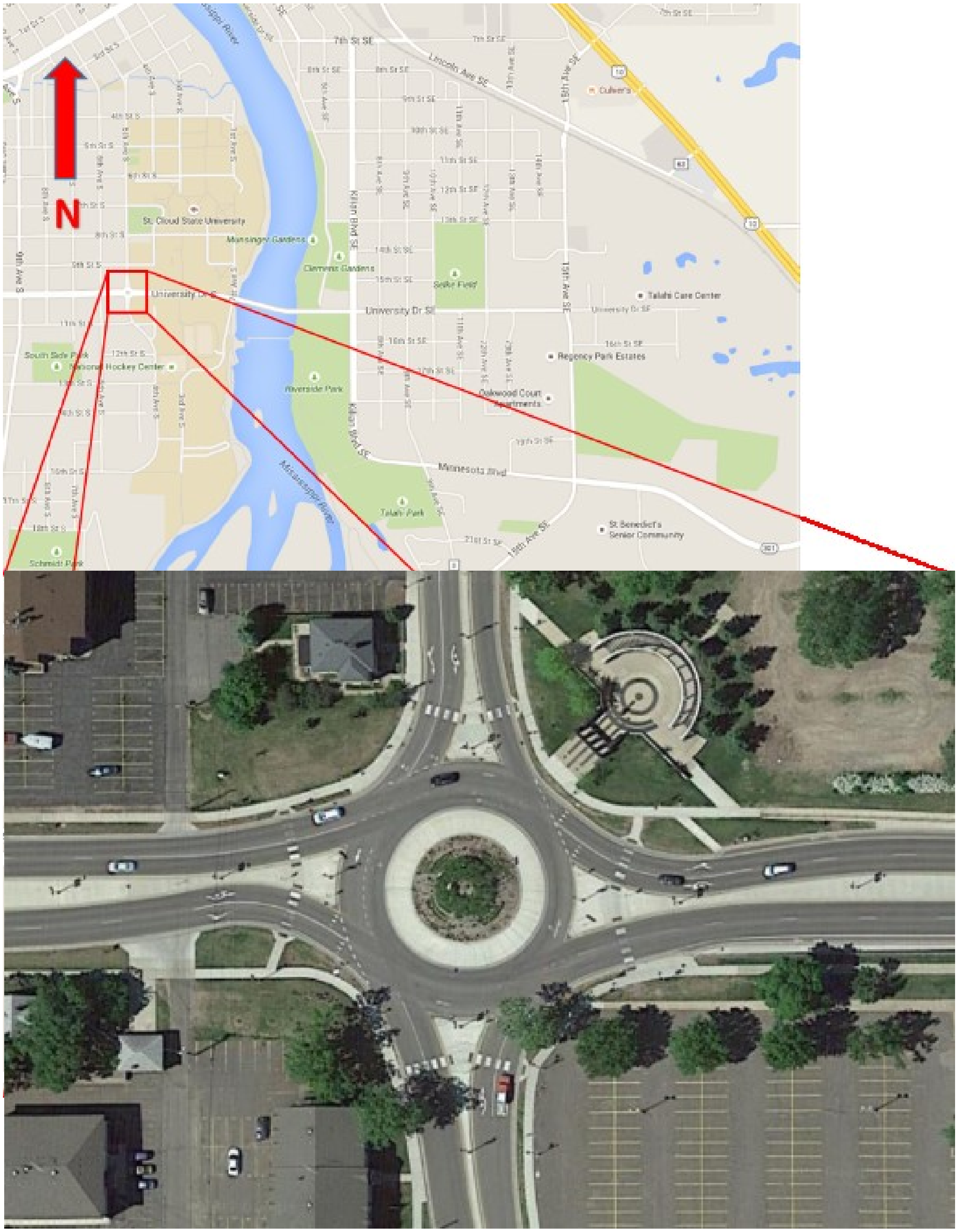

Figure 15. St. Cloud roundabout adjacent to St. Cloud State University

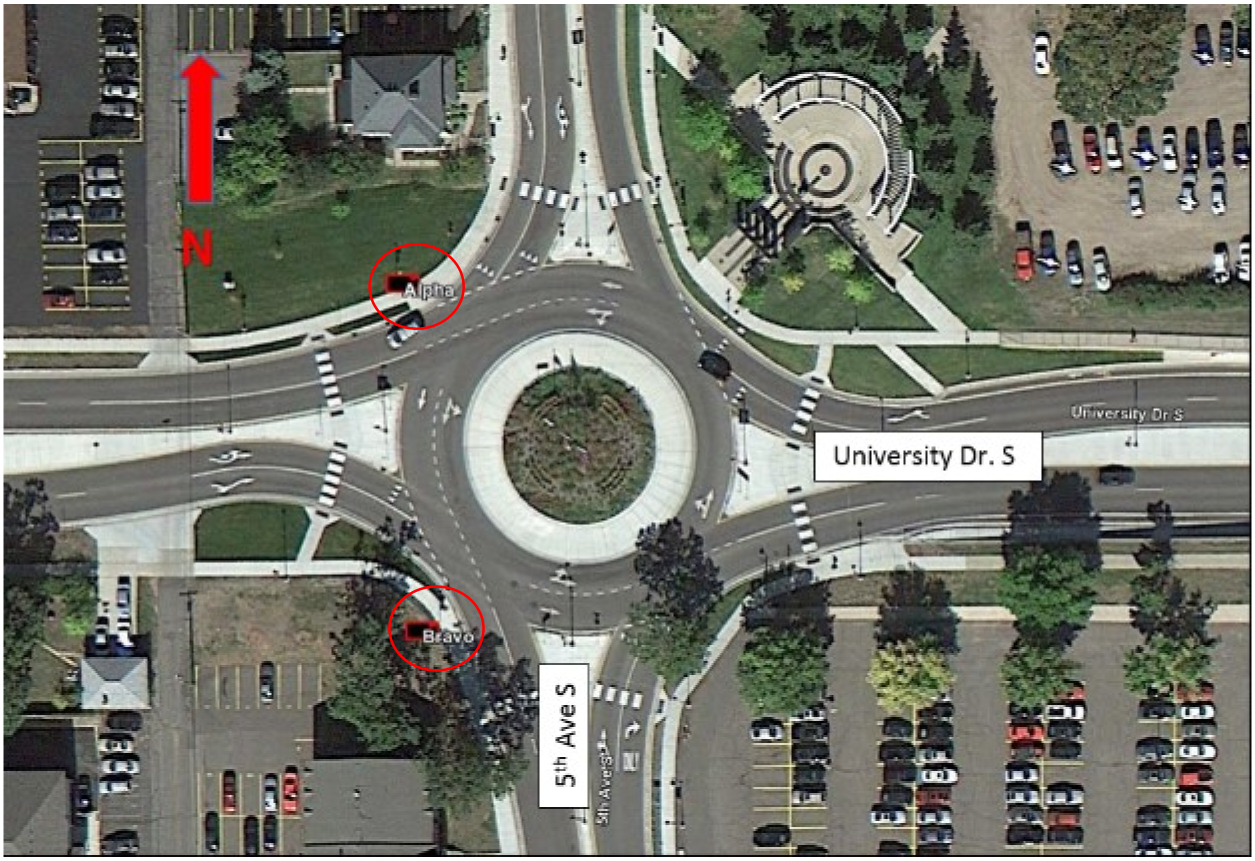

Figure 16. Aerial photo of roundabout at University Drive South and 5th Avenue South in St. Cloud, MN. Note the locations of cameras Alpha and Bravo on the northwest and southwest corners of the intersection.

Figure 17. Video recording station set up with camera pole fully extended (left). Closer view of bracing and security (right)

The cameras at each station were equipped with wide-angle lenses to provide a view of the entire roundabout. The camera at station Alpha on the northwest corner of the intersection was positioned to capture the southbound and westbound approaches and the northern side of the roundabout. The camera at station Bravo on the southwest corner was positioned to capture the northbound and eastbound approaches and the eastern, western, and southern portions of the roundabout. Images from each of these cameras can be seen in Figure 18 and Figure 19, respectively.

Figure 18: View from station Alpha - northern portion of the roundabout.

Figure 19: View from station Bravo – eastern, western, and southern portions of the roundabout.

4.3.1 Observation Periods

The surveillance equipment described above was deployed on March 22nd, 2015, to collect video while classes were still in session at St. Cloud State University. From that date through April 29th, 2015, video data were collected with few interruptions. Recordings focused on the period between 7 AM and 7PM for all days of the week although there were some periods missed due to dead batteries and/or full storage. Figure 20 below includes a breakdown of the recording times captured from each location by date. For each date and station, the start hour and end hour of the video are provided in 24-hour format. Dates with highlighting but no numbers indicate that the full period (7 - 19) was captured, while dates with no highlighting for a station indicate that no video was recorded by that station on that day. In all approximately 32 days of useable video was recorded.

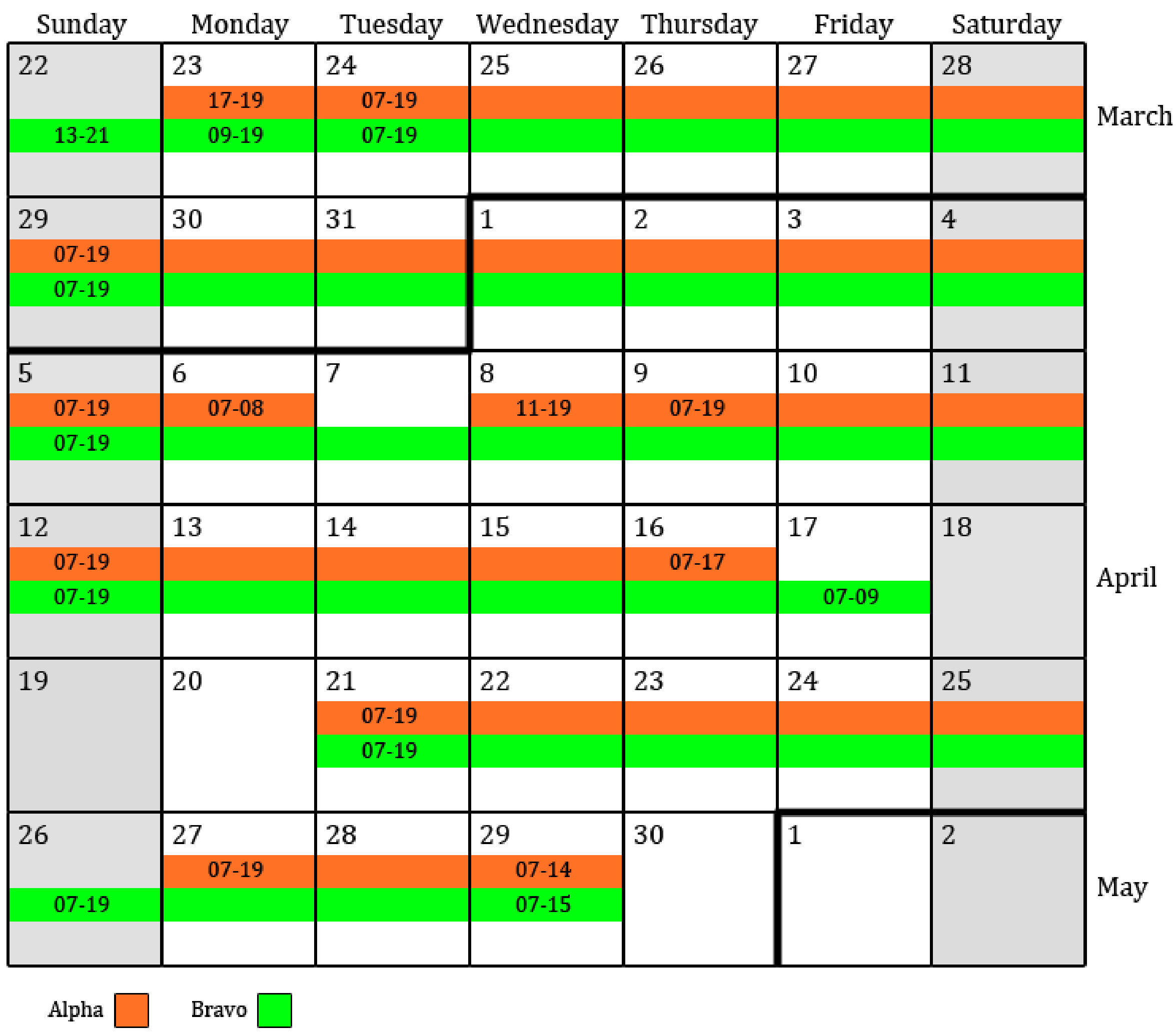

Figure 20: Calendar of video collected at the St. Cloud roundabout over the entire deployment.

4.4 LAKEVILLE

The Lakeville roundabout is located at the intersection of 185th Street West and Kenwood Trail, one mile east of I-35 (Figure 21). The roundabout was first opened for traffic in the Fall of 2015 and the MTO was able to deploy shortly after its completion. This roundabout is a full 2x2 and three cameras were deployed to capture the roundabout. As with the previous data collection sites, the MTO deployed its own field-recording stations to observe this roundabout. One camera was mounted on the southeast corner to capture the southern approach (Figure 24) and two cameras were mounted on the northwest corner to capture the northern approach (Figure 23) as well as capture the entire roundabout in one shot (Figure 22). The latter was installed as a trial to see if the computer vision software could handle the extra distortion caused by the lens being set to its widest view.

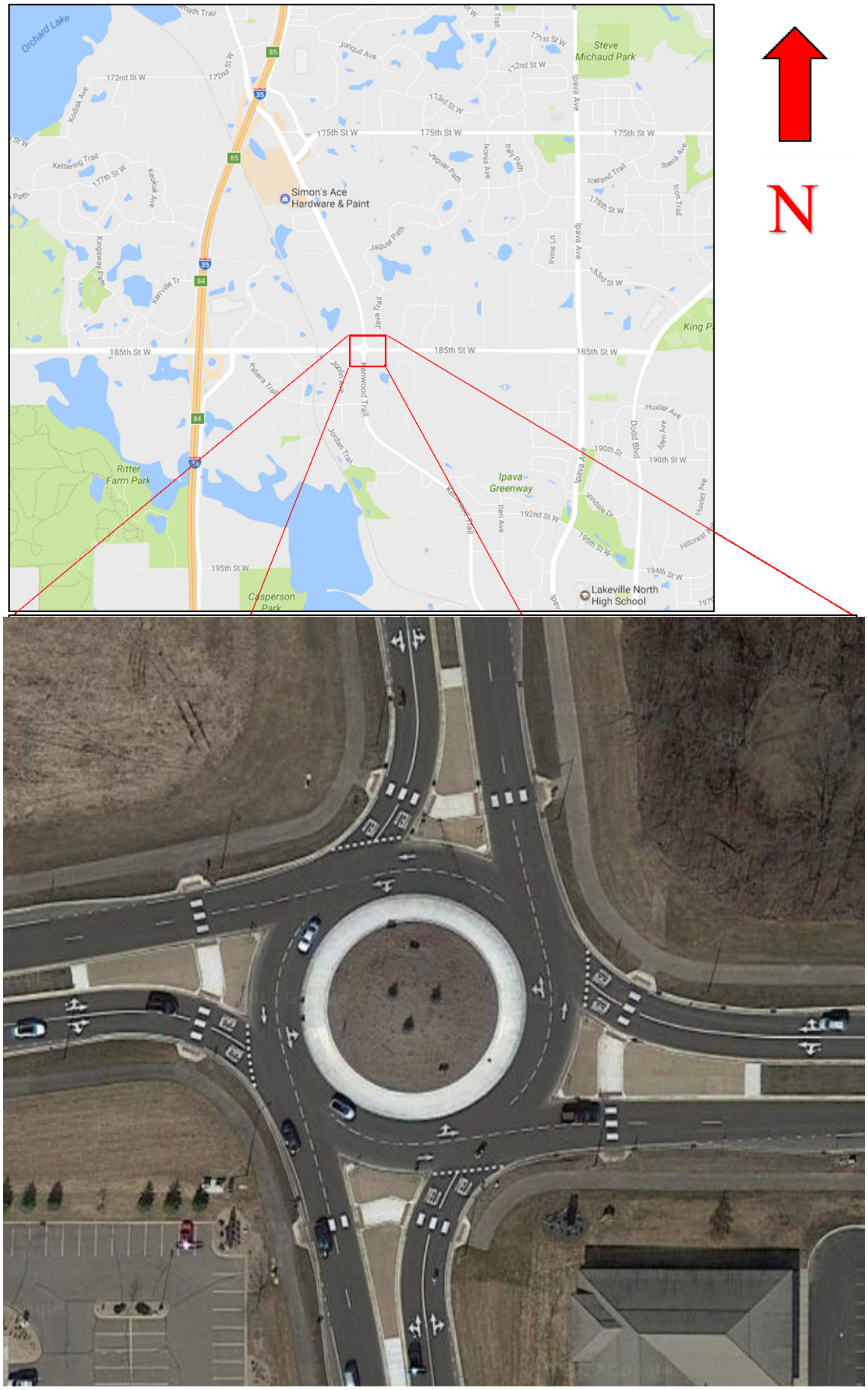

Figure 21: Lakeville roundabout at the intersection of 185th St W (running east/west) and Kenwood Trail (running north/south).

Figure 22: Lakeville Roundabout Camera - Alpha camera - Entire roundabout

Figure 23: Lakeville Roundabout – Hotel Camera - Northwest Quadrant

Figure 24: Lakeville Roundabout - India Camera - Southeast Quadrant

4.4.1 Observation Periods

The surveillance equipment was deployed on November 20th, 2015 through January 2nd, 2016 and video data was collected with few interruptions. Recordings focused on the period between 5 AM and 5 PM for all days of the week, although there were some missed periods due to dead batteries and/or full storage. In all, approximately 43 days' worth of useable video was recorded.

Chapter 5: Data Reduction

This chapter describes the methodology used to extract conflict and violation observations from raw video data. As has been described previously in this report, video was collected at four two-lane roundabouts throughout the state of Minnesota: two in Mankato, one in Lakeville, and one in St. Cloud. To obtain a data set for the statistical analysis, this video was processed using a computer vision trajectory extraction program and trajectory analysis software to populate a database of traffic conflict events and undesirable driving behaviors, along with data on the traffic volume observed at each roundabout, for use in an assessment of safety and mobility at each intersection.

The methodology used for processing the video consists of two preprocessing steps, followed by the application of a roundabout movement and conflict detection model to extract the data that is used for analysis. The purpose of the preprocessing steps is to 1) extract the trajectory data from raw video, and 2) correct the errors that can occur during this process to improve the reliability of the resulting data. The cleaned trajectory data is then processed through the roundabout analysis model to identify and track the vehicles as they move through the roundabout, assessing their behavior and recording the incidents that are relevant to the study. The resulting data includes entry/exit times and turning movements for all of the vehicles observed, along with incidences of improper turns and vehicles failing to yield upon entry.

5.1 TRAJECTORY EXTRACTION

Extraction of trajectory data from video was done using the open-source computer vision program *TrafficIntelligence* (Jackson et. al, 2013), based on the OpenCV library developed by Dr. Nicolas Saunier at Polytechnique Montreal. This program was designed with traffic applications in mind which helps to simplify the process of configuring and calibrating the tracking system, allowing users to spend more time on their particular application. The main configuration step required to use this program with a particular set of video footage is the generation of a homography: a matrix for projecting the coordinates of objects from the perspective of the camera to world space. This step requires an aerial image of known scale (from Google Maps or similar) and a sample camera frame. The user must then select corresponding points in the two images, from which the system calculates the optimal homography that minimizes the total error of the projected points. An example of the points used for generating a homography for one of the sites can be seen in Figure 25.

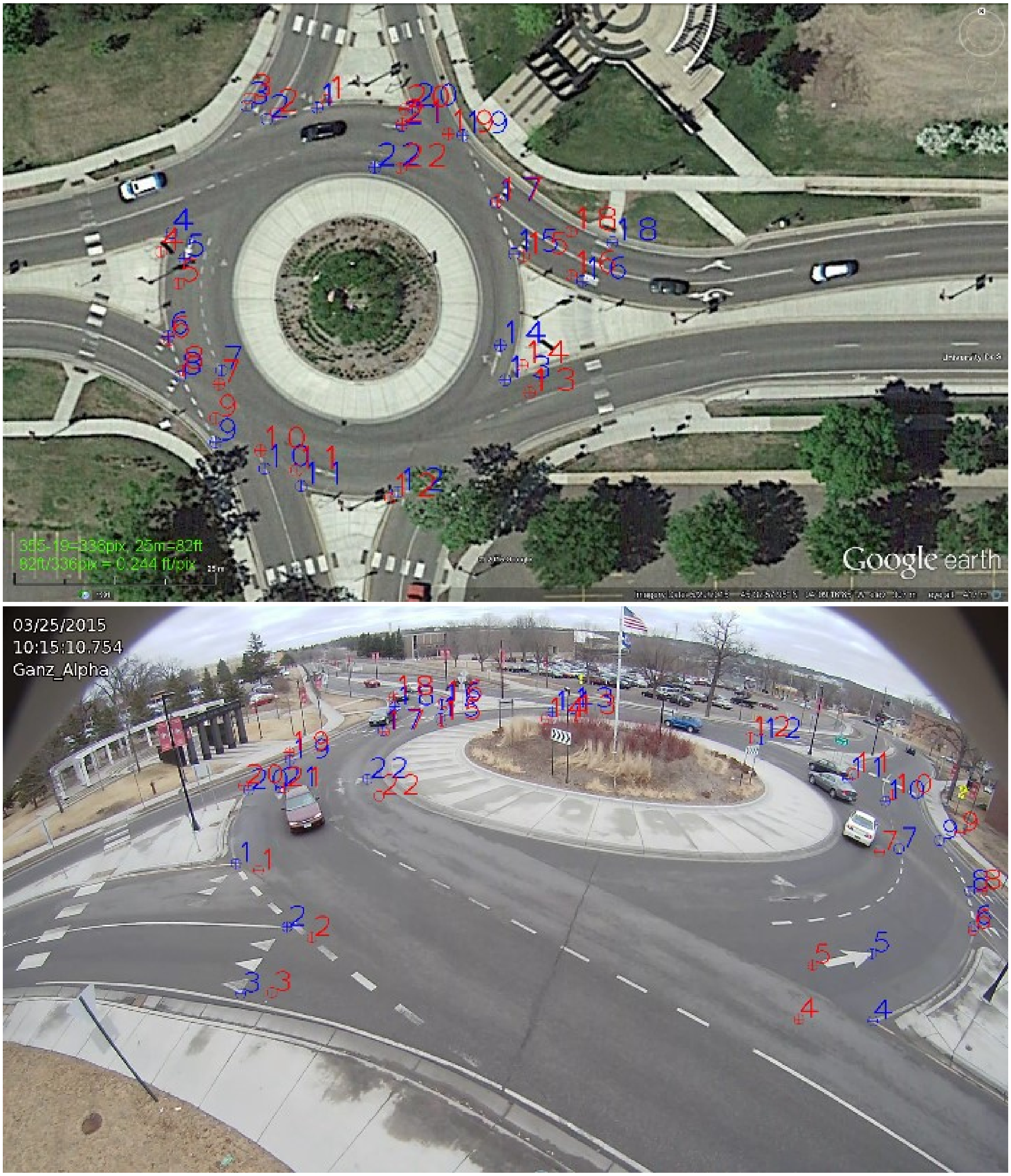

Figure 25 Example of the aerial image (top) and camera frame (bottom) used to generate the homography for the Alpha view of the St. Cloud roundabout.

With the homography generated, TrafficIntelligence (Jackson et. al, 2013) is able to track objects moving in the image in terms of real world units (e.g. feet or meters). This simplifies the process of calibrating the numerical parameters used by the tracking algorithm, since the values are applied after trajectories are projected to world space and can therefore be transferred between different scenes with relative ease. In the event that the parameters do need to be adjusted, as may be necessary if there is a significant change in the video quality or the type of scene being observed, manual calibration of the values is sufficient to obtain the desired results.

Once the configuration and calibration of the TrafficIntelligence has been done for a scene, it generally does not need to be changed unless there is a significant camera shift. The video is then processed in bulk to extract data for the analysis. This step is fairly computationally-intensive, but because the vehicle observations are largely independent, multiple instances of the program can be run simultaneously on one or more machines to decrease the effective processing time. Computers with a good processor can generally extract trajectories from video at a rate faster than real time, with the exact speed dependent mostly on the read speed of the video storage medium.

5.2 CORRECTION OF TRACKING ERROR

The methodology used by TrafficIntelligence to extract trajectories from video uses two passes to generate object trajectories at the level of road users (i.e. vehicles), as opposed to the low-level “features” (small details) that are tracked by the underlying image processing algorithm. This methodology is based mostly on heuristics that use the speed and density of features relative to one another to filter out slow moving objects and group the strongest targets in the image. This behavior can be influenced by adjusting one or more thresholds, however depending on the scene observed it is not always easy to find values that account for all errors that can be made by the system, leaving the user with vehicles that have been erroneously grouped together or individual vehicles represented by multiple trajectories.

In the case of multilane roundabouts, there are some common situations that easily confuse this methodology and lead to this problem. The worst problems arise when vehicles are falsely grouped together near the beginning of their trajectories, causing the estimated vehicle position to jump around on the image when the vehicles ultimately diverge from each other’s path (termed “overgrouping”). The most common situation resulting in this occurs when multiple vehicles enter the roundabout in close proximity and with a similar acceleration profile to one another, as tends to happen whenever two or more vehicles yield to the same vehicle.

To address this issue, a trajectory cleaning methodology that takes advantage of the geometry of the roundabout was devised to identify false groups and break them up to obtain more realistic data. The process works as follows: first, objects are examined at a time later in their trajectory (when their size in the image is largest), then the underlying feature data is probed to determine if the object position is a good representation of the features, as determined by the sum of the squared distance between the object position and each of the features. Objects that fail this test are then broken up using a mean shift clustering algorithm, resulting in data that is much more realistic. An example case of this, showing vehicles before and after the error is corrected, can be seen in Figure 26. Cases of vehicles tracked by multiple trajectories, which occur but are less disruptive to the analysis, are filtered out later during the trajectory analysis based on movement of objects that are close together in space and time.

Figure 26 Example of "overgrouped" objects before (top) and after (bottom) cleaning. Notice how the average position of the single object before cleaning is outside of either of the actual vehicle positions.

5.3 ROUNDABOUT TRAJECTORY ANALYSIS

After vehicle trajectories are extracted and cleaned, they can then be analyzed to interpret their motion in the context of the roundabout. This part of the process requires the user to perform an additional configuration step, defining the lanes of the roundabout in the camera frame, that is necessary to assess whether a vehicle used the correct lanes for their maneuver and if they were involved in any conflicts. Conceptually, the process is divided into two major pieces: the roundabout movement model, where trajectories are analyzed to extract lane use information and conflict detection/evaluation, where the lane-level data extracted by the movement model are used to find and evaluate entrance conflicts.

5.3.1 Roundabout Movement Model

The model developed for interpreting vehicle trajectories relies on a user-created lane configuration, defined by outlining the lanes in the camera frame. A sample of this configuration for each of the views of the roundabouts analyzed in this project can be seen in Figure 27. Using this configuration, the model analyzes the trajectories in a video to determine where the observed vehicles entered and exited the roundabout and which lanes were used in the process. The model has an understanding of what realistic movement through the roundabout looks like, as well as which maneuvers are correct and which constitute an illegal turn (as illustrated in Figure 28 and Figure 29). Unrealistic movement is filtered out to remove potential sources of error; the remaining data, which describes the vehicles that used the roundabout, all the lanes they used, and whether they committed an improper turn. Once this data has been generated, the resulting vehicle data is then processed using the conflict detection and evaluation algorithm to determine which vehicles, if any, failed to yield upon entry and caused a conflict.

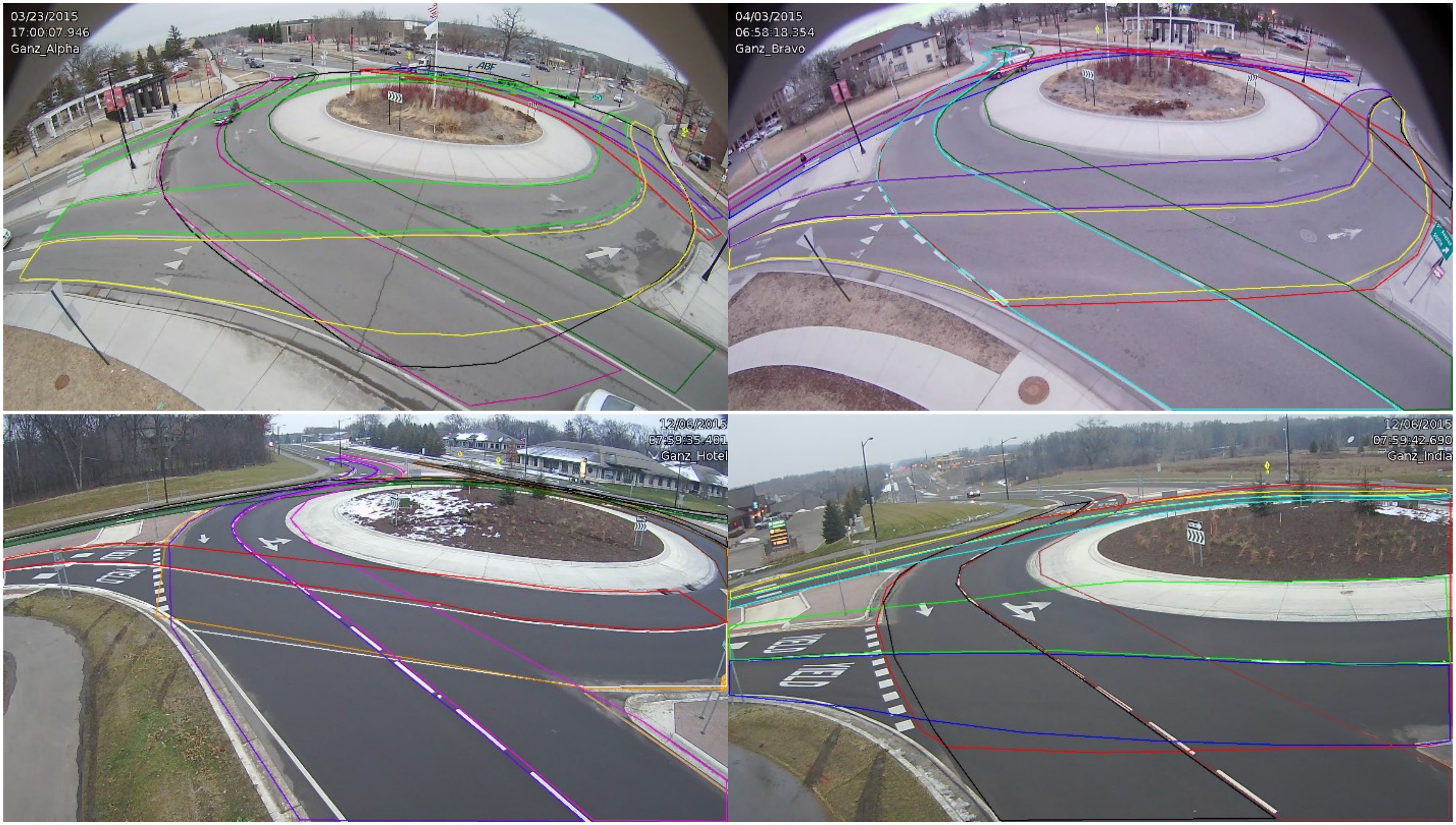
03/23/2015
17:00:07.946
Ganz_Alpha
04/03/2015
06:58:18.354
Ganz_Bravo
12/06/2015
07:59:35.401
Ganz_Hotel
12/06/2015
07:59:42.690
Ganz_India

Figure 27 Sample frames from all views from each of the four roundabouts analyzed; from top to bottom, left to right: St. Cloud Alpha and Bravo, Lakeville Hotel and India, Adams Chanel 1 and Channel 2, and Madison (one camera).

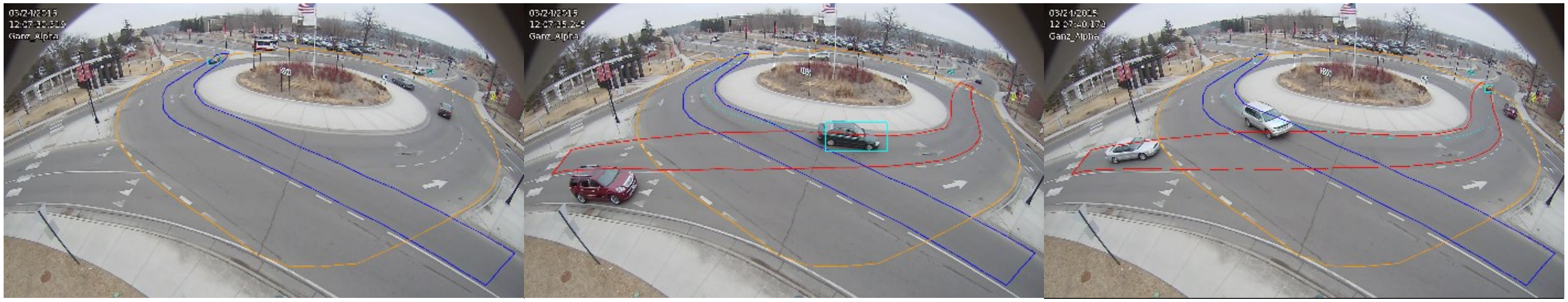

Figure 28 Example of a vehicle moving through the roundabout. The vehicle is observed entering the roundabout in one lane, then seen moving to another lane, then exiting from that lane.

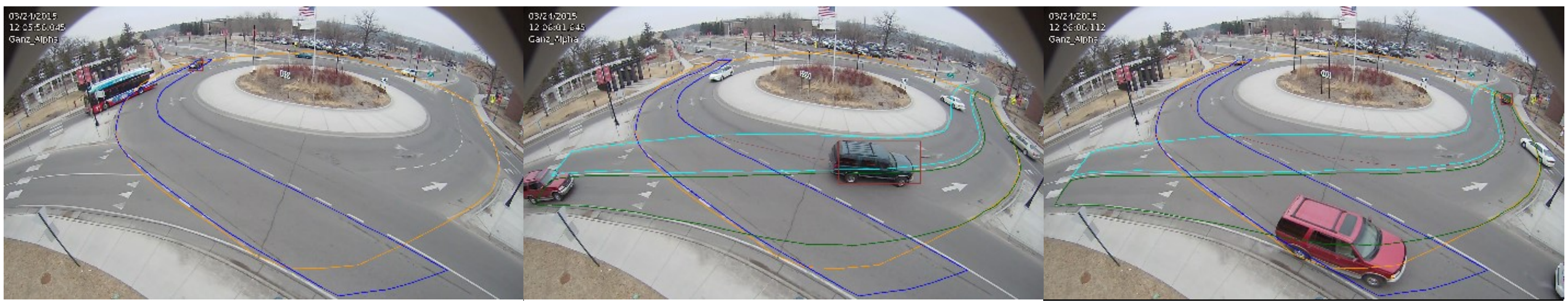

Figure 29 Example of a vehicle making an improper turn in the roundabout. The vehicle is flagged when it is observed making the maneuver from the outer lane to either lane of the next section, crossing over a lane of traffic to do so

5.3.2 Conflict Detection and Evaluation

Once lane information is extracted, the final step is identifying conflicts caused by vehicles failing to yield upon entering the roundabout. This step uses the data generated by the roundabout movement model, where the additional lane use information helps reduce the search space to only cases where such a conflict was possible at all. The potential conflicts are then tested to determine if the event was severe enough to be considered a violation.

Given that speed and distance are critical factors in determining if an event was truly a conflict, there are some challenges in doing so using video data. The primary issue is a consequence of distortion caused by the camera, and particularly the non-linear “barrel distortion” caused by the camera lens. The effect from this can be significant, effectively causing objects in different regions of the image to appear larger or smaller, or appear to move faster or slower, than reality. If this effect is not accounted for, any conflict data extracted from the video will tend to have many false positives in some parts of the frame, and many false negatives in others, both resulting from this non-linear distortion. The effects of distortion can be removed mathematically for the entire image by performing a camera calibration, however this process is fairly advanced and must be redone for each camera/lens combination and focal length.

Instead of this, because of the varied video that was collected for this project and in the interest of making a system that could be easily applied to new roundabouts without a lot of expertise, a different method for working around this problem was devised. Rather than accounting for the distortion directly by calibrating for the specific camera, the effects of the distortion are accounted for in the conflict analysis statistically. This takes advantage of the additional data available from other vehicles using the roundabout to give the system a sense of what “typical” movement through the roundabout looks like, providing a quantification of how much time a vehicle has to enter based on the timing of conflicting vehicles as they pass predefined conflict points (generated automatically from the lane configuration based on intersecting lanes). To generate the data set for evaluating conflicts, every vehicle using the roundabout is measured as it passes through each section. The time taken to traverse a section, and thus arrive at the conflict point with an entrance, is collected along with the initial speed of the vehicle as it entered the section. This data is then aggregated to the approach level so that conflicts at each entrance can be evaluated using the data from the corresponding entrance/conflict region. An example of this measurement is shown in Figure 30.

To test an individual conflict event and determine if it was a violation, this data describing typical movement through the relevant section of the roundabout is used along with the speed of the vehicle as it enters that section. That initial speed of the vehicle is then used with the additional movement statistics to estimate how much time the entering vehicle has until that vehicle should reach the conflict point, recording it as a violation if it is within a threshold that is considered unsafe. It is important to point out here that the only event-specific that influences the test is the initial speed of the vehicle in the roundabout (with right of way), the time they started heading towards the conflict point, and when the entering vehicle has left the conflict region. The primary purpose of modelling the conflict this way is that it eliminates most of the effects caused by the vehicle in the roundabout taking small steps to reduce the probability of a collision, like reducing their speed slightly. This is important because such evasive actions, though small, are often enough to make a conflict appear less dangerous than it was. The test criteria then, in effect, is whether the vehicle with right of way *would have* reached the conflict region before the entering vehicle was safe had they not taken any actions to avoid that. See Figure 31 for an illustration of this concept.

Figure 30 Example of measure lines used to generate statistics of typical movement through the roundabout. Similar measurements are taken at any point where an entrance conflict is possible.

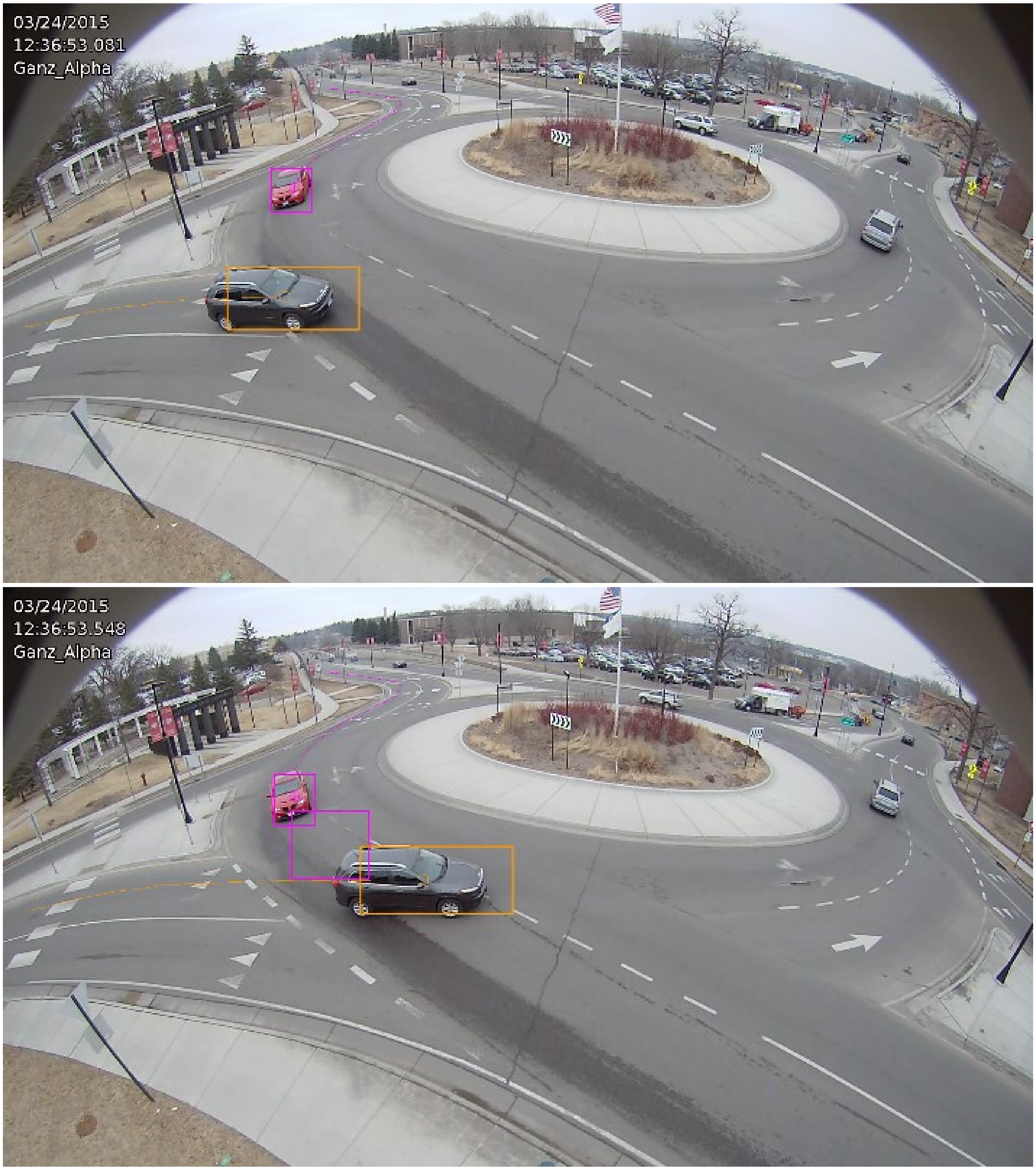

Figure 31 Example of a yield violation as modeled in the system; note the predicted position of the object in the top frame is well within the collision threshold.

Similar to the trajectory extraction, once the configuration has been created, the trajectory analysis can be used to process large amounts of data automatically; the cleaning and analysis code both run in a fraction of the time taken for the trajectory extraction. The final data are saved to a database, which is used to run various statistical analyses, as is described in the next chapter.

Chapter 6: Results

This chapter describes analysis of conflict and violation data obtained from trajectory data extracted from video. Investigations into crash data from these and other roundabouts have highlighted failure-to-yield and illegal turn violations as the most common causes of crashes in two-lane roundabouts. This analysis examined the frequency of these events in each roundabout as compared to the observed volume of vehicles, comparing the results from the different roundabouts and suggesting hypotheses that may explain the observations.

6.1 METHODOLOGY

As stated earlier, data for the analysis were obtained from surveillance footage of each roundabout by running it through a computer vision system to extract violation events and lane-level volume data, details of which can be found in Chapter 7. These data were used to generate normalized violation rates at each location by dividing the total count of each violation type by the relevant volume over the entire analysis period. In the case of yield violations, the total volume from all entrances to the roundabout was used. In the case of turn violations however, only the volumes from the entrances that allow those errors to take place were used; this allows for a fairer comparison of the different roundabouts because of the variations in their designs that make certain maneuvers either impossible or, in at least one case, legal and therefore not a violation.

An important thing to note while looking at these results in the context of the previous study is that, because of the different realities of extracting data manually versus automatically, the rate of yield violations has increased. This is due to the change from a qualitative definition of a yield violation (also referred to as a “Failure-to-Yield” or simply “FTY”) used during the manual reduction process, i.e., whether or not the vehicle in the roundabout exhibited a noticeable reduction in speed, to the quantitative definition used by the computer, which uses a machine-learning technique for identifying conflicts using lane-level speed statistics collected from the video. The definition was made much more restrictive for the manual data reduction to better account for the variation in judgement between the dozens of different observers that were employed on the project over the three-year period, whereas the computer could be relied on to keep its definition constant across the different entrances and locations in a way that can be justified mathematically.

Further on, to better analyze the trends and influences related to yield violations, two specific normalization methods are proposed. In both cases the attempt is to highlight the importance of the two conflicting streams, per lane, involved. The following describe these two methods, namely Normalized – Sum and Normalized – Cross.

Normalized – Sum: $$\frac{\text{FTY Count}}{\text{entrance approach volume} + \text{conflicting circulating volume}}$$

Violation rate as percent of total vehicles meeting at conflict point where entering vehicle fails to yield.

Normalized – Cross: $\frac{\text{FTY Count}}{\sqrt{\text{entrance approach volume} * \text{conflicting circulating volume}}}$

Violation rate as percent of vehicle interaction pairs meeting at conflict point where the entering vehicle fails to yield.

In addition to calculating the total rate of each violation type, yield violation data from each site were examined more closely to determine the distribution of failure-to-yield events among the different cases as determined by the possible combinations of lanes occupied by each of the vehicles involved, with data from all entrances combined together. This allows for more detailed consideration of the factors potentially contributing to the likelihood of each of these cases, especially concerning the signing and/or striping treatments that have been used in attempts to reduce this likelihood. The same breakdown was performed with the data from Richfield, however because of the limitations of the manually-reduced data from that study this was the highest resolution that was allowed.

In contrast, the automatically-reduced data obtained from the sites in the current study allow for an even deeper investigation into the distribution of events by approach, making it possible to test for correlations with features that do not apply to the whole roundabout but only to one or two approaches, for example a high speed limit, unique geometry, or even popular origins/destinations. While no formal investigation into any of these features has been performed at this time, this data has been made available so that such hypotheses could be formed with input from practitioners.

It is important to note that, for the purposes of this report, “circulating” shall refer to a vehicle already within the roundabout which has the right-of-way over entering traffic. “Circulating", for the purposes of this report, does not necessarily indicate that the vehicle is making a left turn rather than exiting.

The results obtained from the analysis performed on each of the locations are presented in the following sections. Results from the previous study in Richfield are also provided for reference. Note that lane changes were not included in the results from the new roundabouts, both because they are not a common cause of roundabout crashes and because of limitations in the current data extraction software that does not differentiate between complete and partial lane changes.

6.2 RESULTS OF PREVIOUS STUDY

As can be seen in Table 2, in the earlier study of the Richfield roundabout, lane changes accounted for the vast majority of violations. However, given that there were almost no crashes attributable to lane change violations, it can be assumed that the frequency of these violations is not a good indicator of the safety of the intersection, justifying the decision to exclude these from the present study.

Table 2. Results of previous study of the roundabout at Portland Avenue and 66th St in Richfield, MN over a 3-year period.

	Count	Normalized Occurrence	Count	Normalized Occurrence	Count	Normalized Occurrence
	Before - 2010 (72 hours)		**After - 2011** (72 hours)		**One Year After -2012** (72 hours)	
Traffic Volume	98015		125078		126044	
Total Violations	5205	5.31%	4918	3.93%	5607	4.45%
Yielding to	1021	1.04%	1065	0.85%	1713	1.36%
Inner	666	0.68%	771	0.62%	1140	0.90%
Outer	300	0.31%	218	0.17%	457	0.36%
Both	55	0.06%	76	0.06%	116	0.09%
Lane Change	3037	3.10%	3095	2.47%	3073	2.44%
Entrance	1301	1.33%	1407	1.12%	1325	1.05%
Exit	1736	1.77%	1688	1.35%	1748	1.39%
Turn Violation	1135	1.16%	750	0.60%	818	0.65%
Right from inner	71	0.07%	77	0.06%	75	0.06%
Left from outer	1027	1.05%	665	0.53%	719	0.57%
More than 270 from outer	37	0.04%	8	0.01%	24	0.02%
Wrong Way	12	0.01%	8	0.01%	3	0.00%
Enter	10	0.01%	8	0.01%	3	0.00%
Exit	2	0.00%	0	0.00%	0	0.00%
Incorrect Lane Choice	1920	1.96%	1152	0.92%	1243	0.99%

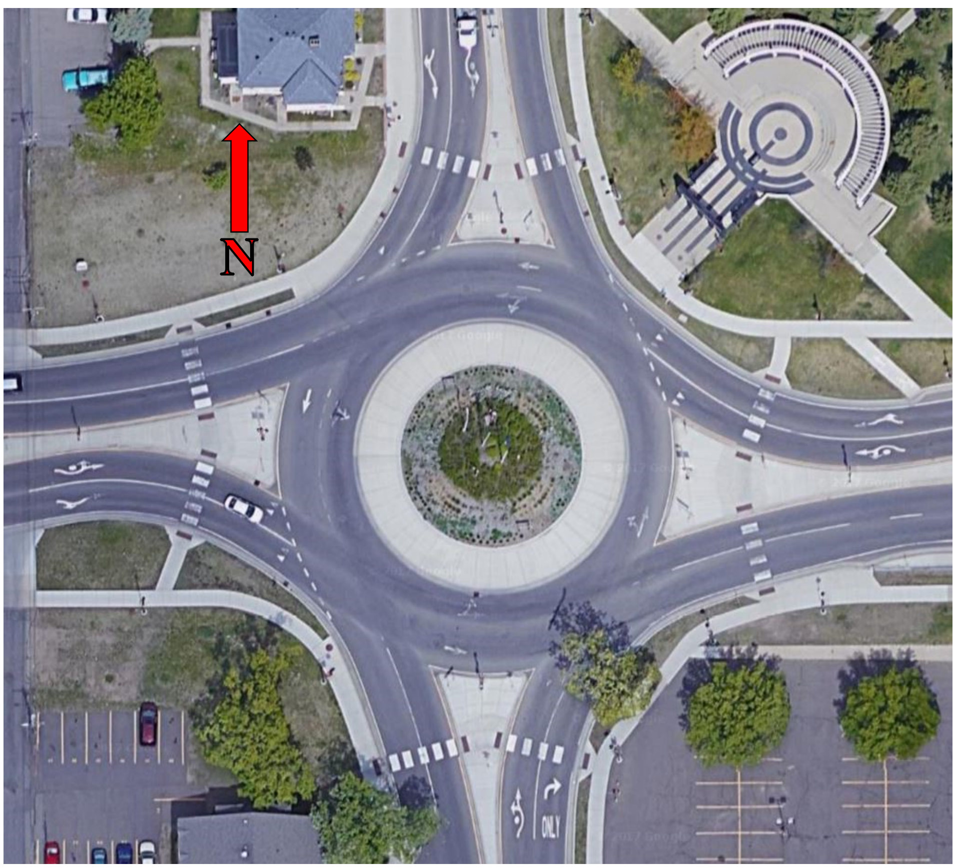

Figure 32 University Dr. S (running east/west) and 5th Ave. S (running north/south) in St. Cloud, MN

6.3 ST. CLOUD

The St. Cloud roundabout carries the greatest resemblance to the Richfield roundabout in terms of build environment, age, road type, and demand. The following numbers are the result of the analysis of 19 days of video observations. Table 3 presents the entering volumes on each approach as total over the 258 hours of collected observations, by entrance lane, and by turning movement while

Table 4 presents the total violation counts per approach. The demand in the St. Cloud roundabout is lower than that of the Richfield roundabout and it has an unbalanced demand with University Drive carrying considerably more traffic than 5th Avenue. The results presented in the subsequent tables attempt to normalize the number of violations observed based on relevant volumes. As noted in each case, more than one normalization version is presented to facilitate deeper understanding of the driver tendencies and interactions that can affect the propensity for violations.

Table 3 Volume in St. Cloud roundabout over entire analysis period by approach, entrance lane, and turning movement. (258 hours)

Entrance Approach	Total Volume	By Entrance Lane		By Turning Movement		
		Inner/Only	Outer	Thru	Left Turns	Right Turns
5th Avenue NB	6,347	6,347	*	4,406	1,757	184
5th Avenue SB	27,748	15,072	12,676	15,253	11,474	1,021
University EB	62,310	38,449	23,861	51,892	7,601	2,817
University WB	70,653	34,988	35,665	54,490	4,251	11,912
Total	167,058	94,856	72,202	126,041	25,083	15,934

*Note that the northbound 5th Avenue entrance has only one lane

Table 4 Volume and violation count by approach and violation type (258 hours)

Approach	Traffic Volume	Yield Violations	Turn Violations	Total
5th Avenue NB	6,347	298	N/A	298
5th Avenue SB	27,748	584	271	855
University EB	62,310	671	117	788
University WB	70,653	928	167	1,095
Total	167,058	2,481	555	3,036

6.3.1 Turn Violations

Whereas left turns from the outer lane were the most common problem in Richfield, in St. Cloud, right turns from the inner lane are a bigger problem, particularly for the southbound and westbound approaches. In both southbound and westbound approaches in St. Cloud, the second lane only starts a short distance from the roundabout which may result in vehicles keeping to the left. More importantly, the higher deflection angles at this roundabout and especially on these two approaches also make it very easy for drivers to commit a right-turn violation by following a relatively straight path.

Table 5 Turn violations observed at St. Cloud roundabout over entire analysis period.

Entrance Approach	Right from Inner Lane				Left from Outer Lane			
	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume
5th Avenue NB	*	*	*	*	*	*	*	*
5th Avenue SB	268	2.34%	0.966%	0.011%	3	0.29%	0.160%	0.002%
University EB	90	1.18%	0.144%	0.043%	27	0.96%	0.054%	0.016%
University WB	97	2.28%	0.137%	0.099%	70	0.59%	0.058%	0.042%
Total	455	5.80%	1.248%	0.153%	100	1.84%	0.272%	0.060%

*No data available for approach due to positioning of cameras

6.3.2 Yield Violations

From the results presented in Table 5 it can be seen that the 5th Avenue SB sum-normalized rate seems to be lower than the rates on the other, which may be misleading given the large difference between the volumes on 5th Avenue and University Drive. The cross-normalized rate attempts to eliminate this imbalance and the result is closer to the rate for the University Drive approaches which implies a non-linear relationship between the circulating volume and the FTY rate. Closer investigation of the lane-by-lane rates presented in Table 7 shows the familiar pattern of higher rates of FTY to the inner lane. This supports the popular notion that drivers often expect vehicles in the inside lane to turn left (continue circulating) rather than exit and thus do not expect the conflict.

Table 6 Yield violations observed in St. Cloud Roundabout by entrance approach and lane.

Entrance Approach	Entrance Lane	FTY to Any Lane		
		Count	Normalized - Sum	Normalized - Cross
5th Avenue NB	Only	298	0.4%	1.6%
	*	*	*	*
5th Avenue SB	Left	231	0.2%	0.5%
	Right	353	0.4%	0.7%
University EB	Left	336	0.4%	0.5%
	Right	335	0.4%	0.5%
University WB	Left	357	0.4%	0.5%
	Right	571	0.7%	0.7%
Total	Left/Only	1,222	1.5%	2.9%
	Right	1,259	1.4%	1.9%

Table 7 Yield violations in St. Cloud Roundabout by entrance approach and the lane of the conflicting vehicle.

Entrance Approach	FTY to Inner/Only Lane			FTY to Outer Lane			FTY to Both Lanes			Total		
	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross
5th Avenue NB	228	0.33%	1.2%	58	0.08%	0.3%	12	0.02%	0.06%	298	0.4%	1.6%
5th Avenue SB	407	0.21%	0.4%	161	0.08%	0.2%	16	0.01%	0.02%	584	0.3%	0.6%
University EB	573	0.32%	0.4%	92	0.05%	0.06%	6	0.003%	0.004%	671	0.4%	0.5%
University WB	928	0.60%	0.60%	*	*	*	*	*	*	928	0.6%	0.6%
Total	2136	0.9%	2.0%	311	0.2%	0.5%	34	0.03%	0.08%	2481	1.11%	2.6%

Table 8 Yield violations in St. Cloud Roundabout by entrance approach, entrance lane, and the lane of the conflicting vehicle.

Entrance Approach	Entrance Lane	FTY to Inner Lane			FTY to Outer Lane			FTY to Both Lanes			Total		
		Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross
5th Avenue NB	Only	228	0.3%	1.188%	58	0.085%	0.3%	12	0.02%	0.06%	298	0.44%	1.6%
	*	*	*	*	*	*	*	*	*	*	*	*	*
5th Avenue SB	Left	138	0.1%	0.3%	89	0.1%	0.2%	4	0.004%	0.008%	231	0.23%	0.45%
	Right	269	0.3%	0.5%	72	0.1%	0.14%	12	0.01%	0.02%	353	0.36%	0.69%
University EB	Left	283	0.3%	0.4%	49	0.06%	0.07%	4	0.005%	0.005%	336	0.4%	0.45%
	Right	290	0.3%	0.4%	43	0.05%	0.06%	2	0.002%	0.003%	335	0.4%	0.45%
University WB	Left	357	0.4%	0.5%	*	*	*	*	*	*	357	0.4%	0.46%
	Right	571	0.7%	0.7%	*	*	*	*	*	*	571	0.7%	0.74%
Total	Left/Only	1,006	1.2%	2.3%	196	0.2%	0.5%	20	0.03%	0.08%	1,222	1.5%	2.9%
	Right	1,130	1.3%	1.7%	115	0.1%	0.2%	14	0.01%	0.03%	1,259	1.4%	1.9%

Table 9 Total volume of vehicles circulating inside St. Cloud roundabout normalized by section volume (258 hours)

Entrance Approach	Circulating Approach	Total Circulating Volume	Circulating Lane Volume			Circulating Lane Volume - Normalized		
			Inner/Only Lane	Outer Lane	Both Lanes	Inner/Only Lane	Outer Lane	Both Lanes
5th Avenue NB	University EB	67,276	37,632	16,420	13,224	55.9%	24.4%	19.7%
5th Avenue SB	University WB	75,402	35,184	20,398	19,820	46.7%	27.1%	26.3%
University EB	5th Avenue SB	29,486	23,220	4,680	1,586	78.7%	15.9%	5.4%
University WB	5th Avenue NB	16,379	16,379			100.0%		

*Note that the northbound 5th Avenue has only one lane in the roundabout

6.4 LAKEVILLE

Figure 33 185th St W (running east/west) and Kenwood Trail (running north/south) in Lakeville, MN

Table 10 presents the entering volumes on each approach as total from 570 hours of observations, by entrance lane, and by turning movement. The demand in the Lakeville roundabout is much higher than the one in Richfield and St. Cloud but in difference to the latter, it has a more balanced demand between approaches. The results presented in the subsequent tables attempt to normalize the number of violations observed based on relevant volumes. Again, more than one normalization method is presented to facilitate deeper understanding of the driver tendencies and interactions that can affect the propensity for violations.

Table 10 Volume by approach. (570 hours)

Entrance Approach	Total Volume	By Entrance Lane		By Turning Movement		
		Inner	Outer	Thru	Left Turns	Right Turns
Kenwood NB	222,061	106,828	115,233			10,672
Kenwood SB	187,773	115,233	72,540	106,477	5,843	75,453
185th EB	168,400	64,963	103,437	51,179	63,200	54,021
185th WB	218,955	112,127	106,828	166,539	13,447	38,969
Total	797,189	399,151	398,038	535,584	82,490	179,115

*Left turns from the northbound Kenwood Tr. entrance were out of frame, so there is no count.

6.4.1 Turn Violations

The following table contains several empty cells. Although the Lakeville roundabout is a has 2x2 conflicts at all four approaches, the positions of the cameras did not allow for reliable extraction of turn violations, in full detail, at all approaches. The turn violation results show a similar distribution to Richfield after the changes where implemented. Specifically, the extended solid lines between entrance lanes were implemented from day one.

Table 11 Turn violations observed in Lakeville roundabout over entire analysis period (570 hours).

Entrance Approach	Right Turn from Inner Lane				Left Turn from Outer Lane			
	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume
Kenwood NB								
Kenwood SB								
185th EB	390	0.7%	0.23%	0.05%				
185th WB					139	1.03%	0.06	0.01%

Table 12 Yield violations in Lakeville Roundabout by entrance approach and the lane of the conflicting vehicle

Entrance Approach		FTY to Inner Lane			FTY to Outer Lane			FTY to Both Lanes			Total (FTY to Any Lane)		
		Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross	Count	Norm - Sum	Norm - Cross
Kenwood NB		2,941	0.4%	0.56%	1,818	0.25%	0.35%	350	0.05%	0.07%	5,109	0.67%	0.98%
Kenwood SB		5,721	0.7%	0.98%	2,038	0.26%	0.35%	258	0.03%	0.04%	8,017	1.0%	1.4%
185th EB	Left										451	0.2%	0.23%
	Right										523	0.22%	0.27%
185th WB													
Total		8,662	1.12%	1.54%	3,856	0.5%	0.7%	608	0.08%	0.1%	13,126	1.7%	2.35%

Table 13 Total volume of vehicles circulating inside Lakeville roundabout (570 hours)

Entrance Approach	Circulating Approach	Total Circulating Volume	Circulating Lane Volume			Circulating Lane Volume - Normalized		
			Inner Lane	Outer Lane	Both Lanes	Inner Lane	Outer Lane	Both Lanes
Kenwood NB	185th EB	270,902	65,999	80,763	124,140	24.4%	29.8%	45.8%
Kenwood SB	185th WB	260,410	104,558	94,038	61,814	40.2%	36.1%	23.7%
185th EB	Kenwood NB							
185th WB	Kenwood SB							

6.4.2 Yield Violations

As presented in

Table 12, the patterns of higher rates of FTY to vehicles in the left (inner) lane of cross traffic is evident in this roundabout also. Results are limited to entrances where the position and angle of the cameras allowed for reliable detection of lane-by-lane movements. Only on one approach, 185th Street EB, was it possible to distinguish between the two entry lanes but it was not possible to distinguish between the two roundabout lanes. In difference, on the Kenwood Trail, approaches it was possible to distinguish between the two roundabout lanes but not between the entering lanes. However, given the produced information, there is no reason to suspect a change of pattern. FTY to both lanes is higher than in St. Cloud and Richfield but the usage of inner and outer lanes is more balanced and incidence of vehicles occupying both lanes at the same time is also higher for one approach compared to St. Cloud. The increased magnitude of violations is likely related to the age of this roundabout at the time of data collection, which was substantially younger than the Richfield and St. Cloud roundabouts.

6.5 MANKATO ROUNDABOUT 1

The observations at both of the Mankato roundabouts started from the first day they were introduced to traffic in September 2014. The results presented here are after two months of operation where it was judged that the learning period was over and the conditions had stabilized. Data were also collected after changes were made to the signs and striping. Table 14 shows the volumes observed during each analysis period by approach, entrance lane, and movement. The analysis focused on highlighting the impact of these changes. Specifically, these changes consisted primarily of adding one-way signs, adjusting the positioning of Yield signs, and adding speed advisory signs.

Figure 34 Adams St (running east/west) and TH-22 (running north/south) in Mankato, MN

Table 14 Adams roundabout: Volume over entire analysis period by approach, entrance lane, and turning movement.

Period	Entrance Approach	Total Volume	By Entrance Lane		By Turning Movement		
			Inner/Only	Outer	Thru	Left Turns	Right Turns
Learning 175 hrs.	Adams EB	21,860	11,888	9,972	242	19,517	2,101
	Adams WB	13,858	13,858		10,440	3,418	
	TH 22 NB	40,180	19,723	20,457	40,180		
	TH 22 SB	51,006	13,198	18,290	31,829	184	18,993
	Total	126,904	58,667	48,719	82,691	23,119	21,094
Before 350 hrs.	Adams EB	73,575	36,908	36,667	746	66,728	6,101
	Adams WB	45,152	45,152		39,329	5,823	
	TH 22 NB	152,689	84,603	68,086	152,689		
	TH 22 SB	106,569	31,190	35,614	59,305	230	47,034
	Total	377,985	197,853	140,367	252,069	72,781	53,135
After 240 hrs.	Adams EB	36,460	21,336	15,124	364	31,793	4,303
	Adams WB	19,907	19,907		19,787	120	
	TH 22 NB	72,565	40,622	31,943	72,565		
	TH 22 SB	62,954	13,843	16,935	31,847	141	30,966
	Total	191,886	95,708	64,002	124,563	32,054	35,269

The geometry of Mankato Roundabout 1 is not a complete 2x2 due to the fact that the Adams Street WB section is one lane. In addition, the Adams Street WB entrance and 5th Avenue NB exit were mostly out of frame, preventing accurate counts of all movements in these sections.

6.5.1 Turn Violations

As can be seen in Table 15, the turn violations follow a similar pattern to the St. Cloud roundabout with a high rate of right-turn violations and a low rate of left-turn violations. At this roundabout, there is only one place where vehicles can commit a left-turn violation, which likely contributes to the low number of them. Right-turn violations, however, can be exacerbated by the high traffic coming from the shopping center where vehicles tend to enter the road close to the roundabout, limiting their time to make the proper lane choice. The changes here did not seem to affect right-from-inner-lane turn violations much as the reduction was very small compared to the number of occurrences. In difference, the left-from-outer-lane turn violations were reduced significantly.

6.5.2 Yield Violations

As shown in Table 16, the entrances from Adams Street have a significantly higher rate of yield violations than the entrances from TH-22. There is no significant difference between the two lanes of a specific entrance. This difference can be due to the speed of vehicles or the availability of gaps but, because the normalized rates are also significantly different, the higher yield violation rates on Adams Street are not due to the differences in demand.

In terms of the lane in which the conflicting traffic is positioned when a yield violation is performed, it was possible to differentiate between the two lanes. Table 16 shows that Mankato Roundabout 1 exhibits the familiar pattern of failure to yield to vehicles in the inner lane as well. Before the traffic control changes, the rates stabilized at a lower level once the learning period had passed. It is interesting to note that after the changes in 2015, yield violation rates climbed up to levels at or above those during the learning period in 2014. No particular explanation can be found for this change.

For completeness, Table 19 presents both the total volume of vehicles circulating inside Mankato Roundabout 1 that would have right-of-way broken down by section and lane and the lane use normalized by section volume.

Table 15 Adams roundabout: Turn violations observed over the 3 analysis periods.

Period	Entrance Approach	Right from Inner Lane				Left from Outer Lane			
		Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume
Learning 175 hrs.	Adams EB	99	4.71%	0.453%	0.078%	*	*	*	*
	Adams WB	*	*	*	*	*	*	*	*
	TH 22 NB	5	0.01%	0.012%	0.004%	*	*	*	*
	TH 22 SB	*	*	*	*	31	16.85%	0.061%	0.024%
	Total	104	4.72%	0.47%	0.082%	31	16.85%	0.06%	0.024%
Before 350 hrs.	Adams EB	231	3.79%	0.314%	0.061%	*	*	*	*
	Adams WB	*	*	*	*	*	*	*	*
	TH 22 NB	28	0.02%	0.018%	0.007%	*	*	*	*
	TH 22 SB	*	*	*	*	30	13.04%	0.028%	0.008%
	Total	259	3.80%	0.33%	0.069%	30	13.04%	0.03%	0.008%
After 240 hrs.	Adams EB	109	2.53%	0.299%	0.057%	*	*	*	*
	Adams WB	*	*	*	*	*	*	*	*
	TH 22 NB	12	0.02%	0.017%	0.006%	*	*	*	*
	TH 22 SB	*	*	*	*	6	4.26%	0.010%	0.003%
	Total	121	2.55%	0.32%	0.063%	6	4.26%	0.01%	0.003%

*The angle and position of the camera did not allow for reliable extraction of turn violations at all entrances.

Table 16 Yield violations in Adams roundabout by entrance approach and lane.

Period	Entrance Approach	Entrance Lane	FTY to Any Lane		
			Count	Normalized – Sum**	Normalized – Cross**
Learning 175 hrs.	Adams WB*	[redacted]			
	Adams EB	Left	732	1.287%	2.106%
		Right	707	1.246%	2.035%
	TH 22 NB	Left	123	0.180%	0.236%
		Right	142	0.207%	0.272%
	TH 22 SB*	[redacted]			
	Total	Left	855	1.466%	2.342%
		Right	849	1.453%	2.308%
Before 350 hrs.	Adams WB*	[redacted]			
	Adams EB	Left	1,444	1.104%	1.569%
		Right	1,522	1.161%	1.649%
	TH 22 NB	Left	498	0.215%	0.272%
		Right	497	0.215%	0.271%
	TH 22 SB*	[redacted]			
	Total	Left	1,942	1.319%	1.840%
		Right	2,019	1.376%	1.920%

After 240 hrs.	**Adams WB***	[redacted]			
	Adams EB	Left	1,144	1.692%	2.353%
		Right	826	1.221%	1.699%
	TH 22 NB	Left	294	0.263%	0.327%
		Right	300	0.269%	0.334%
	TH 22 SB*	[redacted]			
	Total	Left	1,438	1.955%	2.681%
		Right	1,126	1.490%	2.033%

* Limited to entrances where the position and angle of the camera allowed for reliable detection of the entrance lane.

** Rates normalized by the sum of the conflicting volumes (normalized-sum), and rate normalized by the root cross product of the conflicting volumes (normalized-count).

Table 17 Yield violations in Adams Roundabout by entrance approach and the lane of the conflicting vehicle.

Period	Entrance Approach	FTY to Inner Lane			FTY to Outer Lane			FTY to Both Lanes			Total		
		Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross
Learning 175 hrs.	Adams EB**										1439	1.266%	2.071%
	Adams WB*												
	TH 22 NB	204	0.149%	0.196%	59	0.043%	0.057%	2	0.001%	0.002%	265	0.193%	0.254%
	TH 22 SB**										885	0.460%	0.518%
	Total										2,589	1.920%	2.843%
Before 350 hrs.	Adams EB**										2,966	1.133%	1.609%
	Adams WB*												
	TH 22 NB	701	0.152%	0.191%	288	0.062%	0.079%	6	0.001%	0.002%	995	0.215%	0.271%
	TH 22 SB**										1,251	0.295%	0.347%
	Total										5,212	1.643%	2.227%
After 240 hrs.	Adams EB**										1,970	1.457%	2.026%
	Adams WB*												
	TH 22 NB	423	0.190%	0.236%	169	0.076%	0.094%	2	0.001%	0.001%	594	0.266%	0.331%
	TH 22 SB**										185	0.077%	0.088%
	Total										2,749	1.799%	2.445%

* Limited to entrances where the position and angle of the camera allowed for reliable detection of the entrance lane.

** Limited to cases where the position and angle of the camera allowed for reliable detection of the circulating lane.

Table 18 Yield violations in Adams Roundabout by entrance approach, entrance lane, and the lane of the conflicting vehicle.

Period	Entrance	Entrance Lane	FTY to Inner/Only Lane			FTY to Outer Lane			FTY to Both Lanes			Total		
			#	N - Sum	N - Cross	#	N - Sum	N- Cross	#	N - Sum	N - Cross	#	N - Sum	N- Cross
Learning 175 hrs.	Adams WB													
	Adams EB	Left										732	1.287%	2.106%
		Right										707	1.246%	2.035%
	TH 22 NB	Left	98	0.143%	0.188%	25	0.037%	0.048%	0	0.000%	0.000%	123	0.180%	0.236%
		Right	106	0.155%	0.203%	34	0.050%	0.065%	2	0.003%	0.004%	142	0.207%	0.272%
	TH 22 SB													
	Total	Left										855	1.466%	2.342%
		Right										849	1.453%	2.308%
Before 350 hrs.	Adams WB													
	Adams EB	Left										1,444	1.104%	1.569%
		Right										1,522	1.161%	1.649%
	TH 22 NB	Left	363	0.157%	0.198%	131	0.057%	0.071%	4	0.002%	0.002%	498	0.215%	0.272%
		Right	338	0.146%	0.184%	157	0.068%	0.086%	2	0.001%	0.001%	497	0.215%	0.271%
	TH 22 SB													
	Total	Left										1,942	1.319%	1.840%
		Right										2,019	1.376%	1.920%

After 240 hrs.	**Adams WB**													
	Adams EB	Left										1,144	1.692%	2.353%
		Right										826	1.221%	1.699%
	TH 22 NB	Left	209	0.187%	0.233%	83	0.074%	0.092%	2	0.002%	0.002%	294	0.263%	0.327%
		Right	214	0.192%	0.238%	86	0.077%	0.096%	0	0.000%	0.000%	300	0.269%	0.334%
	TH 22 SB													
	Total	Left										1,438	1.955%	2.681%
		Right										1,126	1.490%	2.033%

Table 19 Total volume of vehicles inside Adams roundabout

Period	Entrance Approach	Roundabout Lane	Total Roundabout Volume	Roundabout Lane Volume			Roundabout Lane Volume - Normalized		
				Inner/Only Lane	Outer Lane	Both Lanes	Inner/Only Lane	Outer Lane	Both Lanes
Learning 175 hrs.	Adams EB	TH 22 SB							
	Adams WB	TH 22 NB							
	TH 22 NB	Adams EB	36,054	21,429	14,547	78	59.44%	40.35%	0.22%
	TH 22 SB	Adams WB							
Before 350 hrs.	Adams EB	TH 22 SB							
	Adams WB	TH 22 NB							
	TH 22 NB	Adams EB	104,688	61,373	43,019	296	58.62%	41.09%	0.28%
	TH 22 SB	Adams WB							
After 240 hrs.	Adams EB	TH 22 SB							
	Adams WB	TH 22 NB							
	TH 22 NB	Adams EB	47,834	28,006	19,688	140	58.55%	41.16%	0.29%
	TH 22 SB	Adams WB							

6.6 MANKATO ROUNDABOUT 2

The observations at both of the Mankato roundabouts started from the first day that they were opened to traffic in September 2014. The results presented here are after two months of operation where it was concluded that drivers' learning period was over and the conditions had stabilized. Data were also collected after changes were made to the signs and striping. Table 19 shows the volumes observed during each analysis period by approach, entrance lane and movement. The analysis focused on highlighting the impact of these changes. Specifically, these changes consisted primarily of adding one-way signs, adjusting the positioning of Yield signs, and adding speed advisory signs.

Figure 35 Madison Avenue (running east/west) and TH-22 (running north/south) in Mankato, MN

Table 20 presents the entering volumes on each approach as total from 570 hours of observations broken down by entrance lane, and turning movement. The demand in the Madison roundabout is much higher than those of the roundabouts in Richfield and St. Cloud but, in difference to the latter, it has a more balanced pattern between approaches. The results presented in the subsequent tables attempt to normalize the number of violations observed based on relevant volumes. Again, more than one normalization methods are presented to facilitate deeper understanding of the driver tendencies and interactions that can affect the propensity for violations.

Table 20 Madison roundabout: Volume over entire analysis period by approach, entrance lane, and turning movement.

Period	Entrance Approach	Total Volume	By Entrance Lane		By Turning Movement			Left/Total	Right/Total
			Inner/Only	Outer	Thru	Left Turns	Right Turns		
Learning 740 hrs.	Madison EB	147,003	48,894	50,194	43,862	37,138	66,003	25.26%	44.90%
	Madison WB	111,729	53,228	38,161	55,338	16,649	39,742	14.90%	35.57%
	TH 22 NB	162,983	59,014	68,998	99,796	15,153	48,034	9.30%	29.47%
	TH 22 SB	147,814	66,748	80,700	119,536	18,813	9,465	12.73%	6.40%
	Total	569,529	227,884	238,053	318,532	87,753	163,244	15.41%	28.66%
Before 500 hrs.	Madison EB	54,330	15,214	21,397	16,928	9,469	27,933	17.43%	51.41%
	Madison WB	50,194	25,566	17,675	28,054	6,486	15,654	12.92%	31.19%
	TH 22 NB	50,273	16,614	22,487	34,016	6,062	10,195	12.06%	20.28%
	TH 22 SB	83,857	30,826	34,090	61,250	5,894	16,713	7.03%	19.93%
	Total	238,654	88,220	95,649	140,248	27,911	70,495	11.70%	29.54%
After 260 hrs.	Madison EB	52,255	17,728	17,623	19,635	11,056	21,564	21.16%	41.27%
	Madison WB	38,616	19,205	12,646	19,627	7,170	11,819	18.57%	30.61%
	TH 22 NB	60,197	24,711	23,162	28,201	5,352	26,644	8.89%	44.26%
	TH 22 SB	52,998	24,615	28,332	42,609	7,380	3,009	13.93%	5.68%
	Total	204,066	86,259	81,763	110,072	30,958	63,036	15.17%	30.89%

6.6.1 Turn Violations

Despite having free-right-turn sections, the data shown in Table 21, shows that TH-22 SB shows increased numbers of right-from-inner-lane turn violations. Cases of vehicles making right turns from the left (inner) lane, and thereby traversing two lanes of traffic, have been manually verified. Even though the number of real cases is small and the fact that such a significant error is made by multiple drivers with some regularity, shows that there is a problem communicating proper usage of the roundabout to all drivers. Following the striping and signage changes, there was a sharp reduction of such violations even though none of the changes made focused specifically on this issue. The rate of left-from-outer-lane turn violations is significantly higher, contrary to what was initially thought, although they result in lower crash counts. After the initial learning period, there was a significant drop in occurrences and the rates of turn violations seemed to have stabilized by the time “after” data were collected.

6.6.2 Yield Violations

The number and normalized rates of yield violations in Mankato Roundabout 2 are shown in Table 22 where increased rates of yield violations at the Madison Avenue entrances are not observed. Although the numbers of yield violations from Madison Avenue are numerically higher than the number of violations by vehicles on TH-22, when the demands are considered and normalized rates are calculated, no significant differences are observed.

In terms of the lane in which the conflicting traffic is when the yield violation is performed, it was possible to differentiate between the circulating lanes, Table 22 also shows that, except during the initial learning period, the familiar pattern of relatively high rates of failures to yield to the vehicle in the inner lane of the roundabout is present in Mankato Roundabout 2 as well. Before the traffic control changes, the rates were a little lower than the ones measured after the changes but the difference is small implying that the changes had no significant effect.

For completeness, Table 23 presents both the total volume of vehicles circulating inside Mankato Roundabout 2, i.e. the vehicles that would have right-of-way, broken down by section and lane and the lane use normalized by section volume.

Table 21 Madison roundabout: Turn violations observed over the 3 analysis periods.

Period	Entrance Approach	Right from Inner Lane				Left from Outer Lane			
		Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume	Count	Normalized by Turning Movement	Normalized by Approach Volume	Normalized by Total Volume
Learning 740 hrs.	Madison EB*								
	Madison WB					377	2.26%	0.337%	0.066%
	TH 22 NB*								
	TH 22 SB	761	8.04%	0.515%	0.134%	532	2.83%	0.360%	0.093%
	Total	761	8.04%	0.515%	0.134%	909	5.09%	0.697%	0.160%
Before 500 hrs.	Madison EB*								
	Madison WB					148	2.28%	0.295%	0.062%
	TH 22 NB								
	TH 22 SB	1360	8.14%	1.622%	0.570%	131	2.22%	0.156%	0.055%
	Total	1360	8.14%	1.622%	0.570%	279	4.50%	0.451%	0.117%
After 260 hrs.	Madison EB*								
	Madison WB					82	1.14%	0.212%	0.040%
	TH 22 N*								
	TH 22 SB	110	3.66%	0.208%	0.054%	165	2.24%	0.311%	0.081%
	Total	110	3.66%	0.208%	0.054%	247	3.38%	0.524%	0.121%

*The angle and position of the camera did not allow for reliable extraction of turn violations at all entrances.

Table 22 Yield violations in Madison roundabout by entrance approach and lane of the circulating vehicle.

Period	Entrance Approach	FTY to Inner Lane			FTY to Outer Lane			FTY to Both Lanes			Total		
		Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross	Count	Normalized - Sum	Normalized - Cross
Learning 740 hrs.	Madison EB	2,642	0.244%	0.346%	4,146	0.383%	0.543%	500	0.046%	0.065%	7,288	0.672%	0.954%
	Madison WB												
	TH 22 NB												
	TH 22 SB	973	0.203%	0.257%	1,175	0.245%	0.310%	50	0.010%	0.013%	2,198	0.458%	0.580%
	Total	3,615	0.446%	0.603%	5,321	0.627%	0.853%	550	0.057%	0.079%	9,486	1.130%	1.534%
Before 500 hrs.	Madison EB	651	0.156%	0.225%	525	0.126%	0.182%	38	0.009%	0.013%	1,214	0.291%	0.420%
	Madison WB												
	TH 22 NB												
	TH 22 SB	410	0.159%	0.195%	344	0.133%	0.164%	14	0.005%	0.007%	768	0.297%	0.365%
	Total	1,061	0.314%	0.420%	869	0.259%	0.345%	52	0.015%	0.020%	1,982	0.588%	0.785%
After 260 hrs.	Madison EB	1,073	0.261%	0.376%	857	0.209%	0.301%	78	0.019%	0.027%	2,008	0.489%	0.704%
	Madison WB												
	TH 22 NB												
	TH 22 SB	350	0.197%	0.251%	220	0.124%	0.158%	4	0.002%	0.003%	574	0.323%	0.411%
	Total	1,423	0.458%	0.627%	1,077	0.333%	0.458%	82	0.021%	0.030%	2,582	0.812%	1.115%

* Limited to entrances where the position and angle of the camera allowed for reliable detection of the entrance lane.

** Limited to cases where the position and angle of the camera allowed for reliable detection of the circulating lane.

Table 23 Total volume of vehicles inside Madison roundabout

Period	Entrance Approach	Roundabout Lane Approach	Total Roundabout Volume	Roundabout Lane Volume			Roundabout Lane Volume - Normalized		
				Inner/Only Lane	Outer Lane	Both Lanes	Inner/Only Lane	Outer Lane	Both Lanes
Learning 740 hrs.	Madison EB	TH 22 SB	174,844	53,195	83,049	38,600	30.4%	47.5%	22.1%
	Madison WB	TH 22 NB							
	TH 22 NB	Madison EB							
	TH 22 SB	Madison WB	102,160	52,476	37,202	12,482	51.4%	36.4%	12.2%
Before 500 hrs.	Madison EB	TH 22 SB	69,628	23,220	29,986	16,422	33.3%	43.1%	23.6%
	Madison WB	TH 22 NB							
	TH 22 NB	Madison EB							
	TH 22 SB	Madison WB	48,951	23,600	17,537	7,814	48.2%	35.8%	16.0%
After 260 hrs.	Madison EB	TH 22 SB	71,538	20,670	32,872	17,996	28.9%	46.0%	25.2%
	Madison WB	TH 22 NB							
	TH 22 NB	Madison EB							
	TH 22 SB	Madison WB	37,973	21,634	11,351	4,988	57.0%	29.9%	13.1%

Chapter 7: Conclusions

The study presented in this report is one of the most comprehensive analyses of driving behavior in modern two-lane roundabouts. Four different roundabouts were observed for a long period of time and turning and yielding violations performed by drivers were counted and classified based on their characteristics. The project resources and schedule only allowed for a decent analysis of the available data, but there is still room for a more thorough analysis at a later time. For the same reasons, a few questions generated by the current results remain unanswered. The goal of this report is twofold: to present the reader with the nature of the extracted information so questions on the causal factors behind specific driver behaviors are generated and to present a comprehensive set of summarized results to support old and new conclusions as well as highlight areas where more analysis is needed.

This effort is an expansion of the study performed earlier at the Richfield roundabout. During that study, issues with the comprehension of traffic control devices (markings and signs) were identified and a limited regime of interventions was implemented and evaluated. The interventions focused on the reduction of turn and yield violations that are the cause of the most problematic crashes at multilane roundabouts. Interventions targeting turn violations were successful in reducing left-from-outer-lane violations by more than 50% but no reduction in yield violations was achieved. The following discussion uses the earlier study as a point of reference to identify similarities and differences in violation rates at the four roundabouts investigated in this project.

7.1 TURN VIOLATIONS

Table 24 Summary Comparisons with Richfield Observed Rates (+ higher rate, - lower rate, = similar rate)

	Right-from-Inner-Lane	Left-from-Outer-Lane
St Cloud	+ (++ on 5th Ave Entrances)	- (all single lane links)
Lakeville	+ (on two lane links)	= (- on single lane links)
Adams	-	-- (overhead signs)
Madison	+ (regardless of the free right turn lane)	-- (overhead signs)

The roundabout in St. Cloud presents some differences when compared with the roundabout in Richfield. The rates of right-from-inner-lane violations are much higher in general and on the entrances from 5th Avenue specifically. There is a geometric difference between the two roundabouts, with the St. Cloud one having much greater deflection angles that bring right-turning vehicles on the inner lane on a nearly straight trajectory to the exit. However, left-from-outer-lane violations, which are the source of many of the reported crashes, exhibit noticeably lower rates. Several possible causal factors for this were explored with no revealed correlation. The one geometrical difference in this roundabout is that all roads approaching the roundabout have one lane per direction while, in Richfield, all roads had two lanes per direction. One can hypothesize that, in the case of left turns, drivers instinctively choose to stay close to the left curb and, by extent, the inner lane of the approach. Right-turning drivers seem to do what is more convenient, which in the case of St. Cloud, unfortunately involves right-from-inner-lane violations.

The Lakeville roundabout was the newest of the group, having only been put into operation after the earlier study results were publicized. The engineers tried to incorporate some of the suggestions provided but did not deviate much from the MUTCD guidelines. The right-from-inner-lane violations exhibit higher rates, specifically on the approaches where the upstream links have two lanes per direction. The left-from-inner-lane violations are similar to Richfield, except on the approaches where the upstream direction has one lane per direction. This reinforces the suggestion that drivers originating from single-lane links select the correct entrance lane for left turns. The numbers of both right-from-inner-lane and left-from-inner-lane violations in Lakeville are lower than in St. Cloud; the reason for this may be that the extended solid lines at the entrances proposed in the earlier study were implemented in Lakeville from the start.

The first roundabout in Mankato (Mankato Roundabout 1) is located at the intersection of TH-22 and Adams Street is part of a pair of roundabouts on TH-22 in Mankato. As compared to the earlier study, the right-from-inner-lane violations presented somewhat lower rates that remained relatively steady from the time the roundabout was opened to traffic as well as after the initial learning period was over and following improvements in traffic control. On the other hand, the left-from-inner-lane violations followed significantly different rates after the learning period was over and experienced a noticeable reduction after the traffic control changes. One reason the left-from-inner-lane violations present lower rates may be the use of overhead signs designating the destination of each approach lane. The solid line in the entrances is not as long as recommended by the earlier study, but the overhead lane designation signs seem to serve the same purpose. The other roundabout studied in Mankato (Mankato Roundabout 2) is located at the intersection of Madison Avenue and TH-22 is the second of the Mankato pair and presents a different picture with the right-from-inner-lane violations occurring at much higher rates despite the fact that all entrances have right turn bypass lanes. Specifically, right-from-inner-lane violations in Mankato Roundabout 2 initially occurred at twice the rates of those of Mankato Roundabout 1 but reached similar levels after the changes in traffic control. The traffic control changes did not focus on changes targeting turn violations so it is unclear why the reduction took place. One hypothesis is that the learning period specifically for this type of behavior was considerably longer at Mankato Roundabout 2. However, left-from-inner-lane violations were considerably lower from the start and remained at that level in all study periods, reinforcing the hypothesis that the overhead signs are beneficial.

7.2 YIELD VIOLATIONS

This study has put extra effort into understanding the causes of yield violations since the earlier study failed to produce a traffic control plan that can reduce their rate of occurrence. Unfortunately, this study, too, did not produce insight on the nature of the problem or potential solutions. In the St. Cloud and Lakeville roundabouts, the rates of yield violations followed more or less the same rates as in the earlier study and followed the familiar pattern of higher rates in failures to yield to the inner lane of the roundabout. The failure-to-yield (FTY) rates Mankato Roundabout 1 in the approaches from Adams Street also occurred at similar or slightly higher levels. However, the TH-22 NB approach presented significantly lower rates, almost 10 times lower, while the TH-22 SB approach was somewhere in between. The latter has only one roundabout lane to yield too.

The results are somewhat more complicated at Mankato Roundabout 2. Specifically, the approach from Madison EB exhibited an initial rate that was slightly lower than the norm compared to the earlier study and was sharply reduced after the learning period was over. Unfortunately, in the period after the traffic control changes, it climbed again to nearly the same level as during the learning period though that rate was still lower than the norm. There is no real explanation for this other than the traffic control changes not having the desired effect. The approach from TH-22 SB follows the same pattern as Mankato Roundabout 1, with the FTY rate being significantly lower than any other roundabout in the study and remaining unchanged throughout the three study periods. The conclusion is that the traffic control changes implemented at the Mankato roundabouts did not produce any significant improvements on the yield violation problem.

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